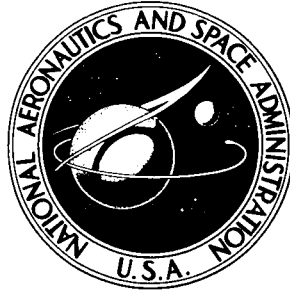


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**COMPUTER PROGRAMS FOR  
PRESSURIZATION (RAMP) AND  
PRESSURIZED EXPULSION FROM  
A CRYOGENIC LIQUID PROPELLANT TANK**

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# COMPUTER PROGRAMS FOR PRESSURIZATION (RAMP) AND PRESSURIZED EXPULSION FROM A CRYOGENIC LIQUID PROPELLANT TANK

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## SUMMARY

An analysis to predict the pressurant gas requirements for the discharge of cryogenic liquid propellants from storage tanks is presented, along with an algorithm and two computer programs. One program deals with the pressurization (ramp) phase of bringing the propellant tank up to its operating pressure. The other program deals with the expulsion of the liquid at a uniform pressure. The method of analysis involves a numerical solution of the temperature and velocity functions for the tank ullage at a discrete set of points in time and space. The input requirements of the program are the initial ullage conditions, the initial temperature and pressure of the pressurant gas, and the time for the expulsion or the ramp. Computations are performed which determine the heat transfer between the ullage gas and the tank wall. Heat transfer to the liquid interface and to the hardware components may be included in the analysis. The program output includes predictions of the mass of pressurant required, the total energy transfer, and the wall and ullage temperatures.

The analysis, the algorithm, a complete description of input and output, and the FORTRAN IV program listings are presented in this report. Sample cases are included to illustrate the use of the programs.

## INTRODUCTION

Planning for space vehicle and mission requirements necessitates continuing optimization of propellant tank pressurization systems. This optimization is realized in an accurate determination of pressurant requirements for any given set of operating parameters, such as tank pressure, inlet gas temperature, liquid outflow rate, and tank size. This knowledge will allow the design of a system that carries only the weight (pressurant gas and associated tankage) necessary to accomplish the mission.

The analysis in reference 1, which is the basis for this report, provides a selected set of simplifying assumptions to predict the quantity of pressurant gas required during the pressurized discharge of liquid hydrogen. Evaluations of pressurant gas injectors based on this work are made in reference 2. These evaluations deal with small-scale tests made in a 0.82-cubic-meter (29-ft<sup>3</sup>) cylindrical tank. The reference 1 analysis proved to be adequate (within  $\pm 10$  percent) in predicting the pressurant gas requirements even though two of its major assumptions were shown to be invalid - namely, no heat transfer to the liquid surface and no mass transfer.

The purpose of this report is to revise and extend the analysis of reference 1 to include the energy transfer occurring at the gas-liquid interface in tanks of any arbitrary symmetric shape. The analysis was also modified and extended to cover the initial pressurization (ramp) period. The major limiting assumptions still remaining from the original analysis are one-dimensional flow and the exclusion of mass transfer.

The algorithm developed in the analysis employs numerical solutions to the gas temperature and velocity functions for the tank ullage at a discrete set of points (in space and time) called net points. Two separate computer programs, coded in FORTRAN IV, are given (each based on the use of a single-component pressurant): one for the pressurized expulsion of a cryogenic (single component) liquid from an axisymmetric storage tank, and the second for the pressurization (ramp) period which may precede an expulsion. The programs are used independently, although they may be coupled together to predict pressurant gas requirements as well as the ullage gas temperature distribution and the adjacent tank wall temperature distribution for the entire pressurization cycle.

Although prior knowledge of the operating conditions for a fluid system is needed for an analysis, the use of the analytical programs does not necessitate that experimental data derived from prototype systems be available.

The validity of the analysis presented herein has been verified in references 3 to 6 for 1.5- and 4-meter (5- and 13-ft) diameter spherical tanks using either gaseous hydrogen or helium as the pressurant over a range of inlet temperatures, tank pressures, and outflow rates. The predicted pressurant requirements for the expulsion period, for all cases, were 7.0 to 12.4 percent of the measured (experimental) values. The predictions for the ramp phase were  $\pm 0.5$  to  $\pm 16.0$  percent of the measured values.

The analysis, the algorithm, a complete description of input and output, and the FORTRAN IV listing are given in this report. Sample cases are included to illustrate the use of the programs.

## ANALYSIS

The general method of analysis is developed in reference 1 and briefly summarized here. The general analytical model is shown in figure 1. It is based on an application of

the first law of thermodynamics to the fluids and materials within a cryogenic-liquid storage tank which has the pressure history shown in figure 2. The first law is represented by a general energy equation which is coupled with a transformed, one-dimensional equation of continuity. Substitutions involving the equation of state and the equation of heat transfer are made to effect the transformation.

In the analytical model shown in figure 1, the ullage volume in a partially filled liquid propellant tank is divided into a set of volume elements. This is done by establishing a series of equally spaced net points along the vertical axis of the tank to the liquid interface. In each volume element, convective heat transfer from (1) gas to wall, (2) gas to liquid, and (3) gas to internal hardware is treated in a steady-state manner by an equation which expresses gas temperature as a function of velocity and position.

The analysis treats the ullage as a single-component gas. For the ramp program, the ullage pressure is made functionally dependent on a discrete set of pressure-against-time coordinates which is submitted as part of the input data. The initial set of net points remains fixed throughout the ramp period and the hold period which may follow. For an expulsion, liquid propellant is expelled, as pressurant gas is added, to maintain the pressure within set limits in the ullage. A new net point is added to the ullage for each time increment necessary to advance the liquid interface as the liquid is discharged.

To determine a unique solution to the velocity and temperature functions at each net point, initial and boundary conditions are specified. These conditions are described fully in the section INPUT-OUTPUT REQUIREMENTS.

The form of the energy equation used in the analysis in reference 1 and modified to account for both arbitrary symmetric tank shapes and internal tank heat sinks may be written as

$$\frac{\partial T}{\partial t} = \frac{2h_c ZRT}{r\bar{M}PC_p} (T_W - T) \left[ 1 + \left( \frac{dr}{dx} \right)^2 \right]^{1/2} - \frac{\bar{V}}{\partial x} \frac{\partial T}{\partial x} + \frac{RTZ_1}{J\bar{M}PC_p} \frac{\partial P}{\partial t} + \frac{\dot{Q}_H}{V\rho C_p} + \frac{\dot{Q}_L}{V\rho C_p} \quad (1)$$

where

$T_W$  temperature of tank wall

$\dot{Q}_H$  heat-transfer rate to internal hardware

$\dot{Q}_L$  heat-transfer rate at liquid interface

(All symbols are defined in appendix A.)

By a substitution involving the equation of state, the one-dimensional equation of continuity is transformed into a functional relation involving the velocity of the ullage gas as a function of temperature and position. For the one-dimensional expression of continuity,

$$\frac{\partial}{\partial x} (\rho \bar{V} A) + \frac{\partial}{\partial t} (\rho A) = 0 \quad (2)$$

The substitution  $A = \pi r^2$  is made, where  $r$  is the position radius at location  $x$  along the vertical axis. The expression for density from the equation of state  $\rho = \bar{M}P/ZRT$  is also substituted:

$$P \frac{\partial}{\partial x} \left( \frac{\bar{V} r^2}{ZT} \right) + r^2 \frac{\partial}{\partial t} \left( \frac{P}{ZT} \right) = 0 \quad (3)$$

The following velocity equation is obtained after performing the partial differentiation and after rearranging terms:

$$\frac{\partial \bar{V}}{\partial x} = \left[ \frac{1}{T} + \frac{1}{Z} \left( \frac{\partial Z}{\partial T} \right)_P \right] \left( \frac{\partial T}{\partial t} + \bar{V} \frac{\partial T}{\partial x} \right) + \left[ \frac{1}{Z} \left( \frac{\partial Z}{\partial P} \right)_T - \frac{1}{P} \right] \frac{\partial P}{\partial t} - \frac{2\bar{V}}{r} \frac{\partial r}{\partial x} \quad (4)$$

Each of the bracketed terms may be simplified by differentiating the equation of state while holding the pressure constant and again while holding the temperature constant.

$$Z_1 = Z + T \left( \frac{\partial Z}{\partial T} \right)_P \quad (5)$$

$$Z_2 = Z - P \left( \frac{\partial Z}{\partial P} \right)_T \quad (6)$$

When the expressions for  $Z_1$  and  $Z_2$  are substituted into equation (4),

$$\frac{\partial \bar{V}}{\partial x} = \frac{Z_1}{ZT} \left( \frac{\partial T}{\partial t} + \bar{V} \frac{\partial T}{\partial x} \right) - \frac{Z_2}{ZP} \frac{\partial P}{\partial t} - \frac{2\bar{V}}{r} \frac{\partial r}{\partial x} \quad (7)$$

where the final term on the right is the contribution of the tank curvature.

The heat-transfer equation at a point in the tank wall can be written

$$\frac{\partial T_W}{\partial t} = \frac{h_c}{l_W \rho_W C_W} (T - T_W) + \frac{\dot{q}_W}{l_W \rho_W C_W} \quad (8)$$

where  $\dot{q}_W$  is the rate of heat addition per unit area to the tank wall from outside the tank.

The equations contained in the analysis are too complex for a closed-form solution. The numerical method used here and described in the algorithm is brought about by approximating the differential equations by algebraic equations. For example, the preceding equation is approximated by

$$\frac{T'_{W,j} - T_{W,j}}{\Delta t} = \left( \frac{h_c}{l_W \rho_W C_W} \right)_j (T'_j - T'_{W,j}) + \left( \frac{\dot{q}_W}{l_W \rho_W C_W} \right)_j \quad (9)$$

where the prime refers to the new value of the variable. Solving the equation for  $T'_{W,j}$  gives

$$T'_{W,j} = \frac{1}{1 + \left( \frac{h_c \Delta t}{l_W \rho_W C_W} \right)_j^*} \left[ T_{W,j} + \left( \frac{h_c \Delta t}{l_W \rho_W C_W} \right)_j^* T'_j + \left( \frac{\dot{q}_W}{l_W \rho_W C_W} \right)_j^* \right] \quad (10)$$

where the quantities marked with the asterisk may be evaluated at the beginning or the end of the time interval. The subsequent algorithms will proceed to show the transformation resulting when  $T'_{W,j}$  from equation (10) is substituted into the algebraic approximation of equation (1). The solution of the resulting transformed equation is coupled to the algebraic approximation of equation (7), and the solution techniques are described.

There are two parts to the algorithm in each computer program. The preliminary part deals with input data and problem definition. The main computation part is concerned with the determination of the amount of pressurant gas added during the expulsion or pressurization period.

The region of the distance-time plane in which the solution is carried out is defined by a set of net points equally spaced along the vertical axis. The entire set of net points is based on an assumed value of a specified number in the initial ullage. From experience, an assigned number of 5 to 6 net points per decimeter (15 to 20 net points/ft) of ullage is satisfactory for nearly all situations and generally provides the desired accuracy for a reasonable computer execution time. Too many net points in the initial ullage may result in using all the available storage for the variables before the expulsion is completed.

## CALCULATION PROCEDURE

### Expulsion Algorithm

A step-by-step description of the basic calculation procedure is given here. Steps 1 to 6 refer to the program listing shown in appendix B under PRELIMINARY COMPUTATION. For the solution to proceed, a set of boundary and initial conditions is required. These conditions are specified in the section INPUT-OUTPUT REQUIREMENTS. Steps 7 to 17 describe the main computation and the results. Figure 3 gives a logic diagram for the expulsion algorithm. A listing of the expulsion program is given in appendix B.

Step 1: make units conversion, make geometry calculations, and interpolate initial wall and gas temperatures and specific heats. - The program is structured so that, at the user's option, the input data are printed out in SI units or in U. S. customary units. First-value parameters are set equal to zero, and values for the constants are computed. The space between the points is established by setting the initial number of net points for the designated initial ullage.

Step 1A begins with a logic statement which provides three basic options to the program user. For a cylindrical tank, the radius is specified. Under this option the program solution is based on a tank with hemispherical end sections joined to the cylindrical midsection, as would be specified in the input data. If the end sections are not hemispherical, the radius is set equal to zero. Input coordinate values are specified (see Group II data in section INPUT-OUTPUT REQUIREMENTS), and the program interpolates the radius for each volume element. The same procedure is followed for spheroidal tanks; however, for a spherical tank, the tank radius is set equal to -1 and the coordinates for each volume element are determined from the tank diameter specified in the input (group I data).

Figure 1 establishes the program model and the tank configuration on a set of coordinate axes. The total number of points selected for the ullage is part of the input data. Although each point is located at the center of its element, each variable associated with the point is representative of the entire element. The distance separating the points, once fixed at the start, remains constant for all points throughout the run time. The first boundary point is at the top of the tank, where  $x = 0$ . The other boundary point is at the liquid-vapor interface, and each boundary element is one-half the thickness of the other elements. For an expulsion the interface is advanced one point for each time step, which is determined by the propellant discharge rate,

$$dt = dx \frac{A(N_Z)}{\left( \frac{M_L}{\rho_L} \right)} \quad (11)$$



For a spherical tank, the radius and flow area for each volume element at the point  $j$  are

$$r_j = \left( Dx_j - x_j^2 \right)^{0.5} \quad (12)$$

$$A_j = \pi x_j (D - x_j) \quad (13)$$

The tank weight for the configuration is approximated by the relation

$$M_T = \sum 2\pi \Delta x l_W \rho_W r_j \left[ 1 + \left( \frac{\Delta r}{\Delta x} \right)^2 \right]^{0.5} \quad (14)$$

The wall thickness  $l_W$  is evaluated by the interpolation subroutine from the discrete values of wall thickness as a function of distance from the top of the tank.

At the initial time ( $t = t_0$ ) the gas temperatures and the wall temperatures as well as the specific heat for each net point in the initial ullage are defined based on a linear interpolation of the input data in step 1C.

Step 2: compute initial values of heat-transfer coefficients. - Gas transport properties at the mean of the gas and wall temperatures for each net point are computed and the free-convection correlation

$$h_c = \frac{k}{L} n(GrPr)^m \quad (15)$$

is employed to evaluate the heat-transfer coefficient at the point. Program options allow for input of multiplier  $n$  and exponent  $m$ . The effect of the flow length  $L$  is canceled when the default value of  $1/3$  is used for the exponent since the length  $L$  is raised to the third power in the Grashof parameter. The pressurant gas properties are included for the subroutines where the computation is made; however, the coefficient  $h_c$  may be specified as a constant for an entire run.

Step 3: compute initial values of  $\dot{q}_W$ ,  $\dot{Q}$  (internal hardware),  $P$ , and  $\Delta P/\Delta t$ . - The outside-wall heating rate, the inside-hardware heating rate, the tank pressure, and its first time derivative are initialized. Typical values in references 3 to 6 are  $\dot{q}_W = 10 \text{ W/m}^2$  ( $0.0009 \text{ Btu/ft}^2\text{-sec}$ ) and  $\dot{Q} = -8.7 \text{ W/m}$  ( $-0.0025 \text{ Btu/sec-lineal ft}$ ). A subsequent option under step 9 is provided in which the energy transferred to the internal tank hardware is computed. The hardware component temperatures are initialized here if the option is taken. If the option is not taken, positive input data values are negated in the program.

Step 4: compute initial value of compressibility factor and then its derivatives which are needed in continuity equation. - The local compressibility factor for the gas temperature and tank pressure, as well as its derivatives, is defined. The equation of state for a real gas is commonly written in terms of a compressibility factor  $Z(P, T)$

$$\frac{1}{\rho} = \frac{ZRT}{MP} \quad (16)$$

Upon differentiating and holding pressure constant,

$$\left[ \frac{\partial}{\partial T} \left( \frac{1}{\rho} \right) \right]_P = \frac{R}{MP} \left[ Z + T \left( \frac{\partial Z}{\partial T} \right)_P \right] \quad (17)$$

where the expression

$$Z + T \left( \frac{\partial Z}{\partial T} \right)_P \equiv Z_1 \quad (18)$$

Differentiating again but with respect to  $P$ , holding  $T$  constant,

$$\begin{aligned} \frac{\partial}{\partial P} \left( \frac{1}{\rho} \right)_T &= \frac{RT}{M} \frac{\partial}{\partial P} \left( \frac{Z}{P} \right)_T \\ &= \frac{RT}{M} \left[ \frac{1}{P} \left( \frac{\partial Z}{\partial P} \right)_T - \frac{Z}{P^2} \right] \\ &= \frac{R}{MP^2} \left\{ -T \left[ Z - P \left( \frac{\partial Z}{\partial P} \right)_T \right] \right\} \end{aligned} \quad (19)$$

where

$$Z - P \left( \frac{\partial Z}{\partial P} \right)_T \equiv Z_2 \quad (20)$$

Step 5: compute initial values of local ullage gas velocities. - The parameters and temperatures evaluated in the previous steps are introduced into a substituted form of the continuity equation. This is obtained by substituting equation (1) into equation (7) and noting that  $\dot{Q}_L$  is zero at time  $t_1 = 0$ . The equation is first solved at the point adjacent to the interface, and the solution is continued from point to point to the top of the tank.

The differential equation (eq. (25), ref. 1) has been modified here to include spherical tanks and approximated at net points ( $x_j$ ,  $t_1$ ) by

$$\begin{aligned} \frac{\bar{V}_{j+1} - \bar{V}_j}{\Delta x} = & \frac{1}{2} \left[ \left( \frac{2h_c Z_1 R}{r \bar{MPC}_p} \right)_j + \left( \frac{2h_c Z_1 R}{r \bar{MPC}_p} \right)_{j+1} \right] \left( \frac{T_{W,j} + T_{W,j+1}}{2} - \frac{T_j + T_{j+1}}{2} \right) \\ & \times \left[ 1 + \left( \frac{\Delta r}{\Delta x} \right)^2 \right]^{1/2} + \frac{1}{2} \left\{ \left[ \left( \frac{RZ_1^2}{\bar{MPZC}_p} - \frac{Z_2}{ZP} \right) \frac{\Delta P}{\Delta t} + \frac{RZ_1 \dot{Q}_H}{\pi r^2 \bar{MPC}_p} + \frac{RZ_1 \dot{Q}_L}{\pi r^2 \bar{MPC}_p} - \frac{2V}{r} \frac{\Delta r}{\Delta x} \right]_j \right. \\ & \left. + \left[ \left( \frac{RZ_1^2}{\bar{MPZC}_p} - \frac{Z_2}{ZP} \right) \frac{\Delta P}{\Delta t} + \frac{RZ_1 \dot{Q}_H}{\pi r^2 \bar{MPC}_p} + \frac{RZ_1 \dot{Q}_L}{\pi r^2 \bar{MPC}_p} - \frac{2V}{r} \frac{\Delta r}{\Delta x} \right]_{j+1} \right\} \end{aligned} \quad (21)$$

Step 6: find gas in ullage at time zero by a numerical integration over ullage density profile. - The mass of the volume elements in the initial ullage is totaled. Since the interface is located at the center of its volume element and the first net point is a boundary condition, by definition, only one-half the masses in these two elements are included in the total.

$$M_U = \int_{V_U} \rho \, dV \approx \sum_{n=1}^{N_f} \rho_n \Delta V_n \quad (22)$$

where  $\rho_n = f(T_n, P)$ .

Step 7: compute initial calculations. - All necessary input data required for the main part of the calculation are now available. The identification of key parameters, along with input and boundary conditions, is important when the output results are reviewed.

Step 8: find temperatures at new time. - When  $T'_{W,j}$  from equation (10) is substituted for the value of  $T_W$  in equation (1),

$$T_j'^2 + \left[ \alpha_j^* \left( 1 + \bar{V}_j^* \frac{\Delta t}{\Delta x} - \omega_j^* \right) - T_{W,j} - \left( \frac{\dot{q}_W \Delta t}{l_W \rho_W C_W} \right)_j^* \right] T_j' - \alpha_j^* \left( \bar{V}_j^* \frac{\Delta t}{\Delta x} T_{j-1}' + T_j \right) = 0 \quad (23)$$

The equation is equation (C1) in references 3 to 6, in which the quadratic is evaluated for the gas temperature  $T_j'$  beginning with the second net point ( $j = 2$ ) at the

top and the value for  $T'_{j-1}$  as the boundary value. The solution to this equation is repeated from point to point until all the ullage temperatures are computed. The value of  $T'_{j-1}$  is always the temperature evaluated at the previous point for the new time. The variable  $T_j$  is the temperature evaluated for the point at the previous time.

The program computes the real positive root of equation (23) by use of the quadratic formula. The wall temperature  $T'_{W,j}$  is also computed under step 8 by equation (10), and the value required for  $T'_j$  is obtained from the gas temperature quadratic (eq. (23)).

Step 9: evaluate energy transfer to internal hardware. - A program option is provided in which the energy transferred to internal tank hardware may be computed. The computed value for step 9 would default any input value. The new hardware temperatures are computed by using the relation

$$T'_H = h_{c,H} A_H \frac{T_{G,j} - T_{H,j}}{(MC_V)_H} \cdot \Delta t + T_{H,j} \quad (24)$$

The heat transferred is then

$$\Delta Q'_1 = \sum_{j=1}^N h_{H,j} (A_{H,1})_j (T_G - T_{H,1})_j \Delta t \quad (25)$$

If four hardware components make up the hardware, the average heat-transfer rate is

$$\dot{Q}_H = \frac{\sum_{t_1}^{t_f} (\Delta Q'_1 + \Delta Q'_2 + \Delta Q'_3 + \Delta Q'_4)}{t_f - t_i} \quad (26)$$

Step 10: find compressibility factors at new time. - In step 10 the compressibility factor and its derivatives are reevaluated based on the new gas temperatures computed in step 8.

Step 11: find velocities at new time. - The new gas velocities are reevaluated by using the new temperature profile and compressibility factors. The finite difference form of equation (4) is used. Although the ullage temperatures are computed starting at the top of the tank, the velocity equation is used to calculate the ullage gas velocity starting with the point  $N_y$  (in fig. 1) near the interface. The velocity at the interface  $N_z$ , the boundary value, is determined from the propellant discharge rate which is part of the input data.

$$\bar{V}'_j = \frac{\left[ T'_j \bar{V}_{j+1} - \left( \frac{Z_1}{Z} \right)'_j \frac{\Delta x}{\Delta t} (T'_j - T_j) + \left( \frac{Z_2}{Z} \right)'_j \frac{T'_j}{P'} \frac{\Delta x}{\Delta t} (P' - P) \right]}{\left[ T'_j + \left( \frac{Z_1}{Z} \right)'_j (T'_{j+1} - T'_j) - 2 \frac{\Delta x}{r_j} T'_j \left( \frac{\Delta r}{\Delta x} \right) \right]} \quad (27)$$

Step 12: find heat flow rate to wall and total heat added to wall; find gas flow rate and total gas added up to new time. - The heat transfer to the tank wall is computed by using the relation

$$Q = M_W C_{v,W} \Delta T$$

$$Q = \sum_j r_j \left[ 1 + \left( \frac{\Delta r}{\Delta x} \right)^2 \right]^{0.5} (T'_{W,j} - T_{W,j}) k_j \quad (28)$$

For the elapsed time  $t_1 \rightarrow t_2$ , the wall temperature changes from  $T_{W,j} - T'_{W,j}$  and

$$k_j = 2\pi \Delta x l_{W,j} \rho_W \quad (29)$$

In step 12, the mass of pressurant in the tank is dependent on the outflow time as well as on the pressurant gas temperature and pressure. The mass of gas in the tank at any time  $t$  during outflow is based on a summation of the mass in all the volume elements in the ullage. The initial mass calculated at the start is subtracted, and the difference represents the pressurant mass added up to time  $t$ .

$$M_U = \int_{t=f}^{t=f} \rho dV - \int_{t=0}^{t=f} \rho dV \approx \sum_{n=1}^{N_f} \rho_n \Delta V_n - \sum_{n=1}^{N_i} \rho_n \Delta V_n \quad (30)$$

An alternate method for determining the flow of pressurant into the tank is provided. The GASCHK parameter measures the velocity of the pressurant passing by an arbitrary area element near the top of the tank. With the gas density evaluated at the element, the mass flow into the tank for a given expulsion is summed over the entire expulsion time.

$$M_U = \sum_{t=i, f} (\bar{v}_n)_t (\rho_n A_n)_t \Delta t \quad (31)$$

Step 13: find specific heats at new time. - The wall and gas specific heats from the top of the tank to the interface are evaluated at the new temperatures.

Step 14: find heat-transfer coefficient at new time. - In step 2 the use of the free-convection correlation is described. The gas-to-wall heat-transfer coefficient is obtained from the same correlation in step 14. This correlation is used for the conditions outlined in references 1 to 7. Reference 8 verifies that the gas-to-wall heat-transfer coefficient is in the free-convection regime for a helium expulsion experiment but reports that it is definitely within the forced-convection regime for oxygen test data. In step 14 this heat-transfer coefficient has been extended to include two component effects, if desired: a forced-convection component, as well as a natural-convection component. The following equations represent the manner in which reference 8 relates both convection components:

Free-convection correlation:

$$\beta_W = 0.00117 r^2 \quad (32)$$

$$h_c = \frac{k}{L} n(GrPr)^m \quad (33)$$

Forced-convection correlation:

$$\frac{h_0 r}{k} = 0.06 \left( \frac{rM}{A_d \mu} \right)^{0.8} \left( \frac{C_p \mu}{k} \right)^{1/3} \quad (34)$$

$$h_{g, W} = h_c + h_0 e^{-\beta_W x} \quad (35)$$

The last term in the combined equation represents the diminishing effect of forced convection as the distance  $x$  increases from the pressurant distributor.

The development of the gas-to-liquid heat-transfer coefficient is given in appendix B of references 3 to 6. It was shown that the conductance across the gas-liquid interface is similar in form to the empirical relation for free-convection flow across a horizontal surface.

$$Nu = \frac{h_{c, L} L}{k} = 0.14(GrPr)^m \quad (36)$$

This equation, with a value of  $m = 1/3$ , is used in step 14 to coincide with the references cited. The heat transferred to the liquid is given by

$$\dot{Q}_L = h_{c,L} A_n (T_\delta - T_{L,S}) \quad (37)$$

in which  $T_\delta$  is a representative temperature at the edge of the thermal boundary layer. For hydrogen or helium pressurant over liquid hydrogen,  $T_\delta$  was determined experimentally to average 1.3 times the adiabatic compression temperature given by

$$T_{ad} = T_0 \left( \frac{P}{P_0} \right)^{(\gamma-1)/\gamma} \quad (38)$$

Although the magnitude of  $\dot{Q}_L$  is computed from a  $\Delta T$  representing a gradient across a gas-liquid interface, the energy transferred to the liquid is represented in the energy equation (1) as being uniformly derived from the entire ullage.

Step 15: check to see if end of time has been reached. - The time increment is computed from the displacement of the interface to the succeeding net point. The time increments are summed to give the elapsed time, which is compared to the time specified for the discharge.

Step 16: end of time exceeded - interpolate conditions at end of time. - When the sum of the time steps has exceeded the specified discharge time, a back interpolation of the computed values is performed to comply with the end of time specified for the discharge.

Step 17: write out results. - The subroutine WRITE 2 is called and the computed values are printed.

### Pressurization (Ramp) Algorithm

A separate computer program determines the mass of pressurant added, as well as tank wall energy requirements, during the ramp and hold periods. The same equations that describe the expulsion period are also applicable for the ramp and hold periods. Even though experimental results (refs. 3 to 6) indicate relatively large amounts of mass transfer during this period, mass transfer and heat transfer to the liquid are not included in the analysis because of the added complexity of the transport process occurring at the interface. A logic diagram for the ramp algorithm is given in figure 4.

The analysis computes the gas temperatures in the ullage at any time during the pressure rise (and hold period) from the gas energy equation. The corresponding gas

velocities are computed from the equation of continuity. An iterative technique is used here which describes how convergence is achieved in the solution for velocity.

The predicted mass of pressurant added is based on a summation of the mass of the volume elements by assuming a one-component ullage consisting of 100 percent pressurant at the end of the ramp and hold periods after subtracting the initial mass at the start. This is explicit for an autogenous pressurization system, for example, where pressurizing gas is derived from an engine jacket bleedoff. For a nonautogenous system, where the pressurizing gas differs from the propellant, a two-component ullage mixture is encountered once ramping is initiated. For a two-component mixture, the contribution to the final pressure by the component gas in the initial ullage is evident from the heat of compression. On a molar basis, the programmed procedure for obtaining the mass addition by the difference of the assumed single-component pressurant in the initial ullage from that in the final ullage would still appear satisfactory. This assumption is verified in references 5 to 7.

Steps 1 to 7: These steps follow the procedure described in the section Expulsion Algorithm, with the exception that hardware component temperatures are not initialized under step 3 since this computational option is not provided. A program listing for the ramp program is provided in appendix C.

Step 8: find temperature at new time, find miscellaneous quantities ( $\dot{Q}_H$  and  $\dot{q}_W$ ) at new time, initialize an estimate for velocity. - The inlet gas temperature representing the upper boundary temperature is defined for the time  $t > 0$ . Likewise, the value of the saturation temperature is defined for the time  $t > 0$  and is made equal to the lower gas boundary temperature at the interface. The boundary wall temperature at the interface is made equal to the bulk propellant temperature.

The option to compute heat transfer to the internal hardware  $\dot{Q}_H$  is not included during the ramp, since this effect during the ramp period is generally small. However, a substituted value for this parameter as well as the outside wall parameter (heat leak rate)  $\dot{q}_W$  may be made a part of the input data.

The initial gas velocity distribution used in solving the temperature function at each net point for each new time  $t$  is obtained from the previous time as follows:

$$\bar{V}'_{t,2} = \bar{V}_{t,1} \frac{\frac{\Delta P_{1-2}}{\Delta t_{1-2}}}{\frac{\Delta P_{0-1}}{\Delta t_{0-1}}} \quad (39)$$

A solution to the ullage temperature function (expressed as a quadratic in the expulsion analysis) under the conditions encountered during ramp proved to be extremely



difficult. When the initial wall temperature distribution in the ullage was greater than the gas temperature distribution, heat transfer from wall to gas resulted in negative velocities, which made it impossible to evaluate the function. A satisfactory method is achieved, however, when the velocity at the net point  $\bar{V}_j^*$  is eliminated from the function. Substituting the velocity function for  $\bar{V}_j^*$  into the quadratic results in the following cubic equation (appendix C of refs. 3 to 6):

$$\begin{aligned}
 b_j T_j'^3 + \left[ \left( \frac{Z_1}{Z} \right)'_j T_{j+1}' + b_j c_j + \alpha_j^* \frac{\Delta t}{\Delta x} (\bar{V}_{j+1}' + d_j) \right] T_j'^2 \\
 + \left[ c_j \left( \frac{Z_1}{Z} \right)'_j T_{j+1}' + \alpha_j^* \frac{\Delta t}{\Delta x} \left( \frac{Z_1}{Z} \right)'_j \frac{\Delta x}{\Delta t} T_j - \alpha_j^* \frac{\Delta t}{\Delta x} T_{j-1}' (\bar{V}_{j+1}' + d_j) - \alpha_j^* T_j \frac{\Delta t}{\Delta x} b_j \right] T_j' \\
 - \alpha_j^* \frac{\Delta t}{\Delta x} \left( \frac{Z_1}{Z} \right)'_j \frac{\Delta x}{\Delta t} T_j T_{j-1}' - \alpha_j^* T_j \left( \frac{Z_1}{Z} \right)'_j T_{j+1}' = 0
 \end{aligned} \quad (40)$$

The main purpose of step 8 is the evaluation of the preceding equation. Unlike the method employed in the expulsion program, the cubic equation is solved numerically by the Newton-Raphson method.

$$(T_j')_f = (T_j')_i - \frac{F(T_j')_i}{F'(T_j')_i} \quad (41)$$

where  $F(T_j')$  represents the cubic function evaluated for the temperature  $T$  at the new time  $(')$  for the point  $j$ . The term  $F'(T_j')$  is its first derivative. The subscript  $i$  for  $T_j'$  represents the initial or previously evaluated temperature in the iterative process and  $(T_j')_f$  is the new value, which has converged closer to the true value (see fig. 5).

Step 9: find heat-transfer coefficient at new time. - Step 9 computes the gas-to-wall heat-transfer (natural convection) coefficient. Steps 9 to 11 together allow for the determination of the thermodynamic and transport properties as a function of  $P$  and  $T$  in the subroutines.

Step 12: find velocities at new time. - The velocity equation used to calculate ullage gas velocity starting with the point  $N_y$  (fig. 1) is the same equation employed in step 11 of the expulsion algorithm. The boundary value of the velocity at the interface, point  $N_z$ , is zero with no expulsion. Figure 5 shows the iteration scheme by which convergence is achieved in the solution of the gas energy and continuity equation.

The ullage gas velocity is calculated from point to point until the top of the tank is reached. The new velocities are used in the cubic equation in step 8 along with the previous values of  $T'_{j+1}$ , and the temperature distribution is redetermined. This process is repeated until the computed velocities are essentially unchanged from those computed in the previous iteration. When convergence is achieved over the entire ullage, the time is then advanced to  $t_2$  and the process is continued as shown in figure 4.

Step 13: find gas flow rate and total gas added up to new time. - Generally, the ramp rate is not accompanied by tank outflow. In step 13, the mass of pressurant in the tank is dependent on the pressurant gas temperature and pressure as a function of ramp time. The mass of gas in the tank at any time  $t$  during the ramp is based on a summation of the mass in all the volume elements in the ullage. The initial mass calculated at the start is subtracted, and the difference represents the pressurant mass added up to time  $t$

$$M_U = \int_{t=f}^{t=0} \rho dV - \int_{t=f}^{t=0} \rho dV \approx \sum_{n=1}^{N_f} \rho_n \Delta V_n - \sum_{n=1}^{N_i} \rho_n \Delta V_n \quad (30)$$

An alternate method for determining the flow of pressurant into the tank is provided. The GASCHK parameter establishes a velocity for the pressurant passing through the second area element from the top of the tank. With the known gas density at the cross section, the mass flow into the tank during the ramp is summed over the entire ramp time. This method generally did not give good agreement with the computed mass derived from the integration of all the volume elements

$$M = \sum_{t=i,f} (\bar{v}_2)_t (\rho_2 A_2)_t \Delta t \quad (42)$$

Step 14: find heat flow rate to wall and total heat added to wall. - This step follows the description for step 12 in the expulsion program.

Step 15: check to see if end of time has been reached. - The time increments are summed to give the elapsed time, which is compared to the specified time for the ramp or hold pressure. In general, ramp has never been experienced with significant tank outflow. However, this possibility does exist, and the time step would then become a function of the discharge rate. Under this condition, the procedure outlined by this step becomes severely constrained. The time involved for the interface to advance to the next point is in many instances too great and results in a serious discontinuity.

Nevertheless, the option to include tank discharge during ramp is provided and may be considered as an extension of the expulsion program with an iteration scheme which may provide some utility for a pressurization system under study.

Step 16: end of time exceeded - interpolate conditions at end of time; and step 17: write out results. - In essence, steps 16 and 17 follow the corresponding steps of the expulsion program.

## SUBROUTINES

The subroutines, which are common to both the pressurization and expulsion programs, are listed in appendix D.

### Subroutine SINTS

SINTS is a subroutine which allows the user the option to program in SI units. This subroutine converts the input data in SI units to the units required by the program.

### Subroutine SPHEAT

The "specific heat" subroutine SPHEAT provides 15 storage locations representing a set of 15 discrete values of specific heat as a function of temperature ( $^{\circ}\text{R}$ ) for the vessel wall, as well as a set of 15 values of specific heat ( $\text{Btu/lbm-}^{\circ}\text{R}$ ) as a function of temperature ( $^{\circ}\text{R}$ ) for the pressurant gas. These data may be substituted to fit the problem definition. The program interpolates values between the points.

### Subroutine WRITE 1

Subroutine WRITE 1 contains the statements which print out the input data.

### Subroutine WRITE 2

Subroutine WRITE 2 contains the statements which print out the problem solution (the calculated pressurant gas and temperature distributions) at any time  $t$  during the expulsion and/or the ramp, following the call statement.

### Subroutine COMPRS

COMPRS is a subroutine which calculates the compressibility factor from a  $20 \times 17$  matrix for hydrogen ( $Z(T, P)$ ). For another gas pressurant the table may be replaced, or a value of  $Z(T, P) = 1.0$  or  $Z(T, P) = \text{Constant}$  may be substituted.

### Subroutine HCOEFF

Subroutine HCOEFF calculates heat-transfer coefficients for either of two pressurant gases (hydrogen or helium) at a specific pressure. Transport property data for each gas are keyed to the molecular weight and may be replaced for other gases.

### Subroutine INTERP

Subroutine INTERP performs a straight-line interpolation between two discrete points.

## INPUT-OUTPUT REQUIREMENTS

### Input

The program input consists of a three-card description of the problem, although any or all of the cards may be blank. Any specific information may be entered in columns 2 to 80, but column 1 is left blank. The succeeding groups of data are defined in the expulsion program listing.

Group I data. - Group I data include the parameters (PARAMS) that relate to tank configuration and input options. These data are entered in NAMELIST FORM.

Group II data. - Group II data are also entered in NAMELIST FORM, which uses names in place of FORMAT numbers in the read (INPNTS) and write (OTPNIS) statements. The INPNTS series is a sequence of coded statements (words) giving the number of pairs of values read in as data which define the initial and boundary conditions for the ramp or expulsion programs. The flexibility of the NAMELIST FORM is demonstrated in the write statement (OTPNIS), which verifies the number of pairs of values that are specified. The number of pairs in each set printed under OTPNIS must agree with the number of paired values in each set submitted under the NAMELIST TABLES that follow. If a single pair is specified under TABLES at time  $t = 0$  (i.e.,  $TGAS = 400.$ ,  $TIME1 = 0.$ ), the value of the variable (TGAS) is maintained constant for any subsequent time.

The expulsion program provides a maximum of 15 data entries under TABLES. The ramp program has the capability of utilizing only the first 11 data entries defined in the following list. The data for MRAD are necessary if the tank radius (as a function of distance from the top) is to be interpolated.

Code	Number of pairs of data
MTGAS	inlet gas temperature (K; °R) as function of time (sec)
MPDATA	tank pressure (MN/m <sup>2</sup> ; lbf/ft <sup>2</sup> ) as function of time (sec)
MFLOW	volume flow rate (m <sup>3</sup> /sec; ft <sup>3</sup> /sec) as function of time (sec)
MTSAT	saturation temperature (K; °R) as function of time (sec)
MTBULK	liquid-propellant bulk temperature (K; °R) as function of time (sec)
MQOUT	outside-wall heating rate (J/m <sup>2</sup> -sec; Btu/ft <sup>2</sup> -sec) as function of time (sec)
MQIN	inside-hardware heating rate (J/m-sec; Btu/lineal ft-sec) as function of time (sec)
MTWIN	initial wall temperature (K; °R) as function of axial distance from top of tank (m; ft)
MTGIN	initial gas temperature (K; °R) as function of axial distance from top of tank (m; ft)
MRAD	tank radius (m; ft) as function of axial distance from top of tank (m; ft)
MTICK	tank thickness (m; ft) as function of axial distance from top of tank (m; ft)
MTBAK	initial temperature of phenolic internal hardware (K; °R) as function of axial distance from top of tank (m; ft)
MTCU	initial temperature of copper internal hardware (K; °R) as function of axial distance from top of tank (m; ft)
MTSS	initial temperature of stainless steel (TP304) internal hardware (K; °R) as function of axial distance from top of tank (m; ft)
MTAL	initial temperature of aluminum internal hardware (K; °R) as function of axial distance from top of tank (m; ft)

Group III data. - The term group III data refers to data that are entered directly into the appropriate subroutine.

### Output

The output from a successfully executed case is written by the subroutine WRITE 2 after a printout of the initial problem conditions by subroutine WRITE 1. This output,

shown for a sample case in appendixes B and C, consists of a block of computed wall temperatures and gas temperatures as a function of distance above the liquid interface.

The block data are preceded by two lines of data. The top line gives the time (TIME) during the ramp or expulsion for which the temperatures are evaluated. Associated with the time, the GAS SUPPLIED, HEAT TO WALL, and INLET VEL (pressurant velocity) are included on the first line. For an expulsion, the second line of output includes the heat transfer to the liquid (propellant). Both programs provide the CHECK ON GAS computation, and the GAS FLOW or rate of pressurant into the tank.

Under group I data, the ENDTIM value specifies the ullage condition at the point in time for the termination. For the ramp program the ENDRMP value represents the ullage condition at the end of the pressure rise period, and ENDTIM represents the condition at the end of the hold period (fig. 2).

The OUTPUT parameter specifies the number of time steps for a "demand" requirement of the computational results.

Two techniques are used to determine the mass of pressurant required for any given time  $t$ . The primary method determines GAS SUPPLIED by summing the product of gas density and volume for all the volume elements for each net time. From this summed value, the initial ullage mass is subtracted. The alternate method, CHECK ON GAS, establishes a velocity for a given cross section near the tank inlet. With the gas density known at the cross section, the mass flow rate into the tank is summed over the entire time.

## TYPICAL ERROR MESSAGES AND THEIR CAUSES

### Ramp Program

Initial ullage velocities are unstable. - Since the wall and gas temperature distributions are specified in the initial ullage, the values for gas specific heat, heat-transfer coefficient, and compressibility factor are defined. The initial velocity at each net point is computed for time  $t = 0$  and  $P = PDATA(1)$ , where  $PDATA(1)$  is the initial pressure throughout the ullage for a series of discrete time-dependent values. This initial velocity distribution is printed out by the program. A negative value for a velocity indicates an incipient instability, and the program terminates itself because of a major overflow. The initial problem condition must be altered by selecting a greater number of net points (smaller net space between points) or by adjusting the initial slope of the pressure rise curve (fig. 1).

Solution to cubic equation requires more than 10 iterations. - Sometimes during the solution for the true ullage temperature, the Newton-Raphson programmed convergence is not achieved in 10 iterations. These occurrences are counted and when the number is

greater than 25, the program reduces the time step and starts the problem again. If the solution is not achieved by this procedure, the pressure rise for the interval is too great, or the instability may be attributed to a large difference between the upper-boundary gas temperature and the inlet pressurant temperature.

One or more negative gas velocities are computed after time zero. - If, during the ramp, one or more negative velocities are computed, the program reduces the time step and starts the problem again. It is programmed to do this three times and then prints out all the gas temperatures in the ullage.

A computed temperature is greater than the boundary temperature. - Sometimes during the course of the solution of the cubic equation, there will be three real and unequal roots. Unfortunately, a distinction cannot be made as to the correct root. When the roots are near the boundary temperature or the inlet temperature, occasionally the converged value may be greater than the value of the inlet temperature. In this predicament, the root can be made equal to the value of the boundary temperature without interrupting the procedure.

Error greater than acceptable (program cannot converge on true ullage temperature). - Path B in the ramp block diagram, shown in figure 4, should not be construed as an alternate program path. It indicates a sequence of printed data values and their relative occurrence during the iterations.

If after 32 iterations, any of the ullage velocities differ from the value computed in the previous iteration by more than 1/2 percent, this condition is indicated by a printout of the velocities.

After 40 iterations, the program may still not converge on the true ullage temperatures. In this circumstance, the deviation of the velocities from those computed in the previous iteration may be greater than 10 percent. This situation is indicated by a printout of the ramp time, ullage temperature, and wall temperature distribution.

These data blocks are printed during steep ramp rates or when extremely nonlinear portions of the ramp curve (pressure rise as a function of time) are encountered. The ramp time parameters PM1, PM2, PM3, and PM4 should be examined and the time step selected accordingly. However, when the time steps are made exceedingly small, excessive computer run times are encountered. Time steps of 0.2 second or less, selected for a large percentage of the total ramp time, may consume more than 1/4 hour of computer time for a 40- to 50-second ramp even though the ullage volume may be only 5 percent of the tank volume.

### Expulsion Program

For the expulsion program, error messages have not been found necessary. In general, if the program is terminated, the reason often appears obvious upon examining the

input data format. If the input data format is correct, a program completion is assured when the initial gas temperature boundaries are equivalent to the liquid interface condition and the pressurant temperature at the start. The wall temperature at the liquid interface should approximate the propellant bulk temperature.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, March 15, 1974,  
502-24.



# APPENDIX A

## SYMBOLS

Engineering symbol	FORTTRAN name	Units in program	Description
A	AREA	ft <sup>2</sup>	Tank cross section normal to vertical axis
-----	AA Y	-----	For cubic equation $y^3 + Py^2 + qy + r = 0$ , $AA Y = (3q - P^2)/3$ .
-----	BEE	-----	$BEE = (2P^3 - 9pq + 27r)/27$
-----	TEST	-----	Evaluate $BEE^2/4 + AA Y^3/27$ to determine the nature of the roots.
b	G8	-----	Coefficient of first term of gas temperature function, eq. (40), represented by cubic equation in ramp program
-----	BQUAD	-----	Second term of quadratic temperature function in expulsion program
C <sub>p</sub>	CP	Btu/(lbm-°R)	Specific heat at constant pressure
C <sub>v</sub> , C <sub>w</sub>	CPW	Btu/(lbm-°R)	Specific heat at constant volume, C <sub>v</sub> ; specific heat of wall material, C <sub>w</sub>
c	G1	°R	$\alpha - \alpha_w - T_w - \frac{\Delta t \dot{q}_w}{l_w \rho_w C_w}$
-----	CQUAD	-----	Final expression of quadratic temperature function in expulsion program
D	DIA	ft	Spherical or cylindrical diameter; vertical diameter when tank is a spheroid
-----	DISC	-----	Discriminant of quadratic temperature function
d	G6	ft/sec	$\frac{Z_2}{Z} \frac{\Delta x}{\Delta t} \left( \frac{P' - P}{P'} \right) - \frac{Z_1}{Z} \frac{\Delta x}{\Delta t}$
Gr	-----	-----	Grashof number, $L^3 \rho^2 g \beta \Delta T / \mu^2$
-----	ERRP	-----	A percent difference in velocity, computed in step 12 (ramp), from value of previous iteration

Engineering symbol	FORTTRAN name	Units in program	Description
g	-----	ft/sec <sup>2</sup>	Gravity acceleration
h <sub>c</sub>	H	Btu/(ft <sup>2</sup> -sec-°R)	Convective heat-transfer coefficient
---	HOPE	-----	Temperature function, cubic in propellant temperature TP
---	ISTAR	-----	Integer representing count of iteration
---	KSTAR	-----	Counting integer - specifies the number of times the numerical solution for a gas temperature could not converge on the true value in 10 iterations
---	KLAMP	-----	Integer counter equal to or less than 3. The ullage temper- ature computations are re- peated so that temperature- dependent parameters are evaluated close to converged gas temperatures.
---	LOOM	-----	Counting integer - if computed value for a gas velocity is less than zero, time step is reduced.
J	XJAY	(ft-lbf)/Btu	mechanical equivalent of heat
L	XL	ft	Flow length
l	TICK	ft	Wall thickness
$\dot{M}$	GSRATE	lbm/sec	Pressurant flow rate addition
$\bar{M}$	XMOLEC	lbm/(lbm-mol)	Molecular weight of pressurant gas
$\Delta M$	GAS (GASB - GSTART)	lbm	Amount of gas (pressurant) added by subtracting initial ullage gas from GASB

Engineering symbol	FORTTRAN name	Units in program	Description
---	GASCHK	lbm	Mass of pressurant added by alternate calculation
$M_U$	GASB	lbm	Summed value of ullage gas over all volume elements for time into ramp or expulsion
m	HEXP	-----	Grashof, Prandtl exponent
N	N, NP	-----	Number of volume segments in tank, NP, refers to next time step
$N_i$ to $N_f$	J	-----	Summing index, i = initial, f = final
$N_1$ to $N_Z$	-----	-----	Particular volume segments
Nu	-----	-----	Nusselt number, $h_c L/k$
$P, P_0$	P, PHOLD	lbf/ft <sup>2</sup>	Tank pressure; initial pressure
$\Delta P$	PP - P	lbf/ft <sup>2</sup>	Differential pressure
Pr	-----	-----	Prandtl number, $C_p \mu/k$
-----	PHE	-----	Coefficient of second term (square in TP) of cubic equation in ramp program
Q	Q, CQTR	Btu	Heat transfer to wall; heat transfer to liquid interface
$\dot{Q}, \dot{Q}_L$	DQ, QTR	Btu/sec	Heat-transfer rate to tank wall; heat-transfer rate to liquid
$\Delta Q1, \Delta Q2$	DQ1, DQ2	Btu	Heat transfer to hardware components 1 and 2
$\dot{q}_W$	QOUT	Btu/(ft <sup>2</sup> -sec)	Heat-transfer rate to wall from outside tank
R	R	(ft-lbf)/(°R)(lbm-mol)	Gas constant
-----	ROOT1	°R	Real positive root of temperature quadratic in expulsion program
Re	-----	-----	Reynolds number, $L\bar{V}P/\mu$
r	RAD	ft	Tank radius
-----	RR	-----	Final term of cubic equation in ramp program

Engineering symbol	FORTTRAN name	Units in program	Description
T	TP, TWP	$^{\circ}\text{R}$	Ullage temperature; tank wall temperature
$T_{L,S}$	TP(N+1)	$^{\circ}\text{R}$	Temperature of the saturated propellant
---	TPP	$^{\circ}\text{R}$	Assigned temperature equal to inlet pressurant temperature
$\Delta T$	TDIFF	$^{\circ}\text{R}$	Differential temperature
$T_{\delta}$	TADD	$^{\circ}\text{R}$	Temperature at edge of thermal boundary layer
t	TIME	sec	Time into ramp, hold period, or expulsion
$\Delta t$	DT	sec	Time increment
---	UU	-----	Coefficient of third term (TP term) of gas temperature function (ramp program)
V	-----	$\text{ft}^3$	Ullage volume
$\bar{V}$	V	$\text{ft}/\text{sec}$	Gas velocity associated with a specific net point
$\Delta V$	-----	$\text{ft}^3$	Volume increment
---	VP	-----	Gas velocity associated with a specific net point at previous iteration
---	VHOLD	$\text{ft}/\text{sec}$	Gas velocity passing volume element near top of tank, used in alternate method of calculating pressurant going into tank
$X_n$	XN	-----	Number of net points in ullage
x	X	ft	Coordinate in direction of tank axis
$\Delta x$	DX	ft	Distance between net points
Z	Z	-----	Compressibility factor
$Z_1$	Z1	-----	$Z + T \left( \frac{\partial Z}{\partial T} \right)_P$
$Z_2$	Z2	-----	$Z - P \left( \frac{\partial Z}{\partial P} \right)_T$

Engineering symbol	FORTTRAN name	Units in program	Description
$\alpha$	D3	$^{\circ}\text{R}$	$\frac{1 + \frac{h_c \Delta t}{\rho_W l_W C_W}}{\left( \frac{2h_c RZ \Delta t}{r \bar{M} P C_p} \right) \left[ 1 + \left( \frac{\Delta r}{\Delta x} \right)^2 \right]^{1/2}}$
$\beta$	BETA	$1/^{\circ}\text{R}$	Coefficient of thermal expansion
$\beta_W$	-----	-----	Dimensional decay coefficient of ullage forced heat-transfer correlation
$\gamma$	-----	-----	Specific-heat ratio
$\mu$	VISC	lbm/(ft-sec)	Viscosity
$\rho$	RHO	lbm/ft <sup>3</sup>	Density
$\omega$	D4	-----	$\left( \frac{R}{\bar{M}} \frac{Z_1}{J} \frac{\Delta P}{\Delta t} + \frac{RZ\dot{Q}_H}{\bar{M}\pi r^2 \Delta x} + \frac{RZ\dot{Q}_L}{\bar{M}\pi r^2 \Delta x} \right) \frac{\Delta t}{C_p P}$

# APPENDIX B

## LISTING OF EXPULSION PROGRAM

```

C      THIS IS THE EXPULSION PROGRAM
C
C
C      *****
C
C      DIMENSION
1      TGAS(30),TIME1(30),PDATA(30),TIME2(30),
2      FLOW(30),TIME3(30),TSAT(30),TIME4(30),
3      TBULK(30),TIME5(30),QOUTD(30),TIME6(30),
4      CIND(30),TIME7(30),ZAV(150),
5      TWIND(30),DIST1(30),TGIND(30),DIST2(30),
6      X(150),T(150),TP(150),TW(150),TWP(150),V(150),
7      CP(150),CPW(150),H(150),Z(150),Z1(150),Z2(150),
8      RAD(150),AREA(150),YRAD(150),XRAD(150),DRDX(150)
C
C      DIMENSION
1      C5(150),C9(150),YTICK(50),XXT(50),TICK(150)
2      ,TWBK(30),DIST7(30),TWCU(30),DIST8(30),TSTN(30),DIST9(30),
3      TWAL(30),DIS11(30),CPBK(150),TWB(150),TB(150),CPCU(150),
4      TWC(150),TC(150),CPST(150),TST(150),TZ(150),CPAL(150),
5      TALS(150),TBC(150),TTT(150),PRAM(150)
C
C      COMMON
1      X,T,TP,TW,TWP,V,CP,CPW,TGAS,TIME1,MTGAS,PDATA,TIME2,MPDATA,
2      FLOW,TIME3,MFLOW,TSAT,TIME4,MTSAT,TBULK,TIME5,MTBULK,QOUTD,
3      TIME6,MQOUT,QIND,TIME7,MQIN,N,NP,XN,ULLAGE,RADIUS,DQ,
4      SPWGT,XMOLEC,GSTART,HCONST,TIME,GAS,Q,GASCHK,GSRATE,DT,
5      ZCONST,H,HMULT,HEXP,YRAD,XRAD,MRAD,TNKWT,CQTR,QIN,UNUMS,
6      MTWIN,MTGIN,MTICK,MTBAK,MTCU,MTSS,MTAL,
7      TWIND,DIST1,TGIND,DIST2,YTICK,XXT,TWBK,DIST7,
8      TWAL,DIS11,TWCU,DIST8,TSTN,DIST9
C
C      COMMON
1      CARAD,ADIFU,SPWSS,DIA,RCONST,TADD,AB,A1C,A3S,A5B,WTB,WT1C,
2      WT3S,WT5B
C
C      *****
C
C      READ 3 CARDS OF PROBLEM DESCRIPTION AND WRITE OUT.  THERE
C      MUST BE THREE CARDS USED, ALTHOUGH ANY OR ALL OF THEM MAY
C      BE BLANK.  LEAVE THE FIRST COLUMN OF EACH CARD BLANK AND
C      ENTER ANY INFORMATION IN COLUMNS 2 TO 80.
C
1      WRITE (6,100)
      DO 2 J=1,3
      READ (5,101)
      WRITE (6,101)
C
C

```

```

C      NOMENCLATURE FOR INPUT DATA
C      *****

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```

C      XN,          NET POINTS AT TIME ZERO (MUST BE 3 OR MORE)
C                  NET POINTS AVAILABLE 150 (SEE DIMENSION STATEMENTS)
C                  REQUIRED INPUT GROUP I DATA
C      OUTPUT,     NUMBER OF TIME STEPS TAKEN BEFORE EACH OUTPUT
C      ULLAGE,     INITIAL ULLAGE HEIGHT, (CANNOT BE ZERO)
C      RADIUS,     TANK RADIUS
C      IF RADIUS = 0, THE RADIUS IS INTERPOLATED BASED ON THE TANK RADIUS
C      (VS DISTANCE FROM TOP) DATA READ INTO THE PROGRAM.
C      IF RADIUS = -1, THE TANK IS A SPHERE (DIA = DIAMETER)
C      SPWGT,      TANK WALL SPECIFIC WEIGHT
C      SPWSS,      SPECIFIC WEIGHT OF TANK LID MATERIAL
C      ENDTIM,     TIME AT WHICH OUTFLOW ENDS, SECONDS
C      XMOLEC,     MOLECULAR WEIGHT OF PRESSURIZING GAS
C      ZCONST,     COMPRESSIBILITY FACTOR (1. FOR IDEAL GAS, BLANK FOR REAL)
C      HCONST,     HEAT TRANSFER COEFF. (BLANK IF H IS TO BE CALCULATED)
C                  IF HCONST IS BLANK H WILL BE COMPUTED FROM THE EQUATION
C                   $H = HMULT * COND/XL * (GRASHOF * PRANDTL)**HEXP$ 
C      HMULT,      CONSTANT IN ABOVE EQUATION (0.13 IS USED IF LEFT BLANK)
C      HEXP,       CONSTANT IN ABOVE EQUATION (0.333 IS USED IF LEFT BLANK)
C
C      DIA,        DIAMETER WHEN THE TANK IS A SPHERE OR CYLINDER.
C                  SPECIFY DIAMETER ON VERTICAL AXIS WHEN TANK IS SPHEROID
C      RCONST,     INITIAL HEIGHT USED IN CALCULATION OF H
C      TR1,TR2     GOVERNS THE MODE OF TRANSFER BETWEEN PRESSURANT GAS AND
C                  TANK WALL. IF TR2 IS BLANK AND TR1=1., HEAT TRANSFER
C                  IS BY FREE CONVECTION, IF TR2=1., TR1 IS BLANK, HEAT
C                  TRANSFER IS BY FORCED CONVECTION
C      TADD,       A TEMPERATURE AT THE EDGE OF THE THERMAL BOUNDARY
C                  LAYER TO DETERMINE THE DRIVING POTENTIAL, (TADD-TSAT).
C                  FOR HYDROGEN PRESSURANT OVER LIQ H2, TADD WAS DETERMINED
C                  EXPERIMENTALLY TO BE 1.2-1.5 TIMES THE ADIABATIC
C                  COMPRESSION TEMPERATURE
C                  SEE NASA TN D-5336, 5387
C      UNUMS       SET GREATER THAN 0. FOR SI UNITS
C      *****
C      QQQQ,       IF QQQQ IS BLANK, PROGRAM ASSUMES NO INTERNAL HARDWARE
C                  UNLESS THE QIND VS TIME7 VALUES ARE GIVEN UNDER INPUT
C                  DATA. IF QQQQ=1, THEN SOME OR ALL PARAMETERS
C                  AB THRU WT5B ARE SPECIFIED
C
C      AB,         EFFECTIVE AREA PHENOLIC HARDWARE EXPOSED TO THE
C                  PRESSURANT GAS IN THE VOLUME ELEMENT
C      A1C         EFFECTIVE AREA OF COPPER HARDWARE EXPOSED TO THE
C                  PRESSURANT GAS IN THE VOLUME ELEMENT
C      A3S,        EFFECTIVE AREA OF THE 304 SS HARDWARE EXPOSED TO THE
C                  PRESSURANT GAS IN THE VOLUME ELEMENT
C      A5B,        EFFECTIVE AREA OF ALUMINUM HARDWARE EXPOSED TO THE
C                  PRESSURANT GAS IN THE VOLUME ELEMENT
C      WTB,        WEIGHT OF THE PHENOLIC HARDWARE IN THE VOLUME ELEMENT
C      WT1C,       WEIGHT OF COPPER HARDWARE IN THE VOLUME ELEMENT
C      WT3S,       WEIGHT OF 304SS HARDWARE IN THE VOLUME ELEMENT
C      WT5B,       WEIGHT OF ALUM. HARDWARE IN THE VOLUME ELEMENT

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C          OPTION 2 DATA
C
C      DIC.          PARAMETER USED IN CALCULATING GAS TO WALL,
C                    FORCED CONVECTION HEAT TRANSFER
C      ADIFU         PRESSURANT DISTRIBUTOR AREA
C      CARAD.        CHARACTERISTIC RADIUS OF THE TANK WHEN FORCED CON-
C                    VECTION IS A MODE OF HEAT TRANSFER
C      END OF OPTION II DATA
C      BEXPO. MBEXPO  PARAMETERS INVOLVING DECAY COEFFICIENTS
C                    SEE NASA TM X - 53165
C
C
C          GROUP I DATA
C      NAMELIST / PARAMS / XN,OUTPUT,ULLAGE,RADIUS,SPWGT,ENDTIM,XMOLEC,
C      1HCONST,DIA,RCONST,ZCONST,HMULT,HEXP,AB,AIC,A3S,A5B,MTB,MT1C,
C      2WT3S,WT5B,SPWSS,QQQU,TADD,DIC,TR1,TR2,CARAD,ADIFU,CYLN,UNUMS
C      READ(5,PARAMS)
C
C          GROUP II DATA  EXPULSION DATA- CONTINUED
C      *****
C      NAMELIST / INPNTS / MTGAS,MPDATA,MFLOW,MTSAT,MTBULK,MQOUT,MQIN,
C      1MTWIN,MTGIN,MRAD,MTICK,MTBAK,MTCU,MTSS,MTAL
C      READ(5,INPNTS)
C      NAMELIST / OTPNTS / MTGAS,MPDATA,MFLOW,MTSAT,MTBULK,MQOUT,MQIN,
C      1MTWIN,MTGIN,MRAD,MTICK,MTBAK,MTCU,MTSS,MTAL
C      WRITE(6,OTPNTS)
C      NAMELIST / TABLES /
C      1 TGAS  , TIME1  , PDATA  , TIME2  , FLOW   , TIME3  ,
C      2 TSAT  , TIME4  , TBULK  , TIME5  , QOUTD  , TIME6  ,
C      3 QIND  , TIME7  , TWIND  , DIST1  , TGIND  , DIST2  ,
C      4 YRAD  , XRAD  , YTICK  , XXT   , TWBK   , DIST7  ,
C      5 TWCU  , DIST8  , TSTN   , DIST9  , TWAL   , DIST11
C      READ (5,TABLES)
C
C          GROUP III PROPERTY DATA-SEE SUBROUTINE-
C      NOTE - THE DATA BLOCKS IN THE SUBROUTINES MAY BE SUBSTITUTED FOR
C            DIFFERENT GASES OR WALL MATERIAL CONSISTENT WITH
C            HYDROGEN/HELIUM BEHAVIOR.
C      1 - SUBROUTINE SPHEAT - MATERIAL AND GAS SPECIFIC HEATS
C          NOTE -- THE SPECIFIC HEAT SUBROUTINE FOR HYDROGEN
C                HAS NO PROVISION FOR PRESSURE VARIATION
C          NOTE -- THE WALL SPECIFIC HEAT DATA IN THE SUBROUTINE
C                DOES NOT PROVIDE STORAGE FOR MORE THAN ONE MATERIAL
C      2 - SUBROUTINE COMPR - GAS COMPRESSIBILITY
C      3 - SUBROUTINE HCOEFF - TRANSPORT PROPERTIES
C
C      *****

```



C  
C

ITER1=0  
Q=0.  
GASCHK=0.  
H2H=0.0  
QTR=0.0  
CQTR=0.0  
TAKWT=0.0  
GSTART=0.  
DO1=0.

# PRELIMINARY COMPUTATION

TITLE		PROJECT NUMBER		ANALYST		SHEET		OF																																																																									
FORTAN STATEMENT																																																																																	
STATEMENT NUMBER	CONT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
<p>TEST CASE TO EXAMINE THE HARDWARE OPTION USING SI UNITS</p> <p>CYLINDRICAL TEST SECTION - CIRCUMFERENTIAL ALUM. BAFFLES</p> <p>100 SECOND EXPULSION - 0.61 METER TANK RADIUS</p> <p>\$PARAMS</p> <p>XN=1.5, OUTPUT=1.0, ULLAGE=3.249168, RADIUS=0, SPWGT=2803.231,</p> <p>ENDTIM=100, XMOLEC=2, HCONST=0, DIA=1.21920, RCONST=0.3249168,</p> <p>ZCONST=0, HMULT=0, HEXP=0, AB=0, A1C=0, A3S=0, A5B=0.825788,</p> <p>WTB=0, WTIC=0, WT3S=0, WTB=0.01061406, SPWSS=2803.231, QQQQ=1.,</p> <p>TADD=0, DIC=0, TRI=1, TR2=0, CARAD=0, ADIFU=0, CYLN=3.249168,</p> <p>UNUMS=1.0 \$END</p> <p>\$INPUTS</p> <p>MTGAS=1, MPDATA=1, MFLOW=1, MTSAT=1, MTBU LK=1, MQOUT=0, MQIN=0, MTWIN=2,</p> <p>MTGIN=2, MRAD=2, MTICK=2, MTBCK=2, MTBAK=0, MTCU=0, MTSS=0, MTAL=2 \$END</p> <p>\$TABLES</p> <p>TGAS=2.77, TIME1=0, PDATA=6.9774942, TIME2=0,</p> <p>FLOW=.02845843, TIME3=0, TSAT=29.222, TIME4=0,</p> <p>TBULK=20.833, TIME5=0, QOUT=0, TIME6=0,</p> <p>QIND=0, TIME7=0, TWIND=55.555, 20.8333, DIST1=0, 3249168,</p> <p>TGIND=163.888, 29.222, DIST2=0, 0.3249168,</p> <p>YRAD=.6096, 60.96, XRAD=0, 3.249168,</p> <p>YTICK=4.32816E-05, 4.32816E-05, XXT=0, 3.249168,</p> <p>TWAL=55.555, 20.8333, DIST1=0, 0.3249168 \$END</p>																																																																																	
<p>NASA-C-836 (REV. 9-14-59)</p>																																																																																	

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      DQ2=0.
      DQ3=0.
      DQ4=0.
C
      CALL WRITE1
C
      IF (UNUMS .EQ. 0. ) GO TO 301
      CALL SINTS
301  CONTINUE
      XPI=3.14159
      R=1545.4
      XJAY=778.2
      HCCNST=HCONST/3600.
      N=XN
      NP=N+1
C
      DX=ULLAGE/(XN-1.0)
      IWRITE=OUTPUT
C
C
      DIFU = SORT(4.*ADIFU/XPI)
      C8=R/XMOLEC
      C3 = DX * C8
      C1 = C3/2.
      C2 = C1/XJAY
      C4 = DX/C8
      C6 = 2.*C8
      C7 = C8/XJAY
C
C
      DO 3 J=2,150
      XJTICK=J-1
      X(J)=DX*XJTICK
      CALL INTERP (YTICK,XXT,MTICK,X(J),TICK(J))
      C5(J)=1.0/(TICK(J)*SPWGT)
3    C9(J)=2.0*XPI*DX*TICK(J)*SPWGT
      X(1)=0.0
      TICK(1)=YTICK(1)
C
C
C
C          STEP-1A-
      MAKE GEOMETRY CALCULATIONS
      IF (RADIUS) 8,4,6
4    DO 5 J=2,150
      CALL INTERP (YRAD,XRAD,MRAD,X(J),RAD(J))
5    AREA(J)= XPI*RAD(J)**2
      RAD(1)=RAD(2)
      AREA(1)=AREA(2)
      GO TO 12
C
6    CONTINUE
      DO 7 J=2,150
      IF (X(J) - DIA/2.) 199,299,299
199  RAD(J) = SQRT(DIA * X(J) - X(J)**2)
      AREA(J) = XPI * RAD(J)**2
      GO TO 7

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299 IF(X(J) .GT. (CYLN + RADIUS)) GO TO 399
   RAD(J) = RADIUS
   AREA(J) = XPI * RAD(J)**2
   GO TO 7
399 PLEG = X(J) - CYLN - RADIUS
   IF(PLEG .GE. RADIUS) GO TO 499
   RAC(J) = SQRT(RADIUS**2 - PLEG**2)
   AREA(J) = XPI * RAD(J)**2
7   CONTINUE
499 RAD(1) = RAD(2)
   AREA(1) = AREA(2)
   GO TO 12
8   DO 10 J=2,150
   IF (X(J)-DIA) 9,9,11
9   RAD(J) = SQRT(DIA * X(J) - X(J)**2)
10  AREA(J)=XPI*X(J)*(DIA-X(J))
11  AREA(1)=AREA(2)
   RAD(1)=RAD(2)
C
12  CONTINUE
   DO 16 J=2,149
13  DRDX(J)=(RAD(J+1)-RAD(J))/(X(J+1)-X(J))
C
C   TANK WEIGHT DOES NOT INCLUDE WEIGHT OF LID OR CONNECTOR AT TOP
C
15  TNKWT = TNKWT + C9(J)*RAD(J)*SQRT(1.0 + DRDX(J)**2)
16  CONTINUE
17  DRDX(1)=(RAD(2)-RAD(1))/X(2)
   DRDX(150) = DRDX(149)
   DT=DX*AREA(N)/FLOW(1)
   CALL INTERP (FLOW,TIME3,MFLOW,DT,FLO)
   DT=DX*AREA(N)/((FLOW(1)+FLO)*2.0)
   VP=FLOW(1)/AREA(N)
   TIME=DT
C
C   STEP-1B-
C   COMPUTE INITIAL WALL AND GAS TEMPERATURES
C
DO 19 J=1,N
18 CALL INTERP (TWIND,DIST1,MTWIN,X(J),TW(J))
   CALL INTERP (TGIND,DIST2,MTGIN,X(J),T(J))
C
C   STEP-1C-
C   COMPUTE INITIAL VALUES OF SPECIFIC HEAT
C
19 CALL SPHEAT (T(J),TW(J),CP(J),CPW(J),XMOLEC)
C
C   STEP-2-
C   COMPUTE INITIAL VALUES OF HEAT TRANSFER COEFFICIENT
C
IF (HCONST) 1,22,20
C
20 DO 21 J=1,150
21 H(J)=HCGNST
   GO TO 31

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```

C
22 IF (HMULT) 1,23,24
23 HMULT=0.13
C
24 IF (HEXP) 1,25,26
25 HEXP=0.333
C
26 DO 30 J=1,N
    IF (X(J)-RCONST) 27,27,28
27 XL=DIA
    GO TO 29
28 XL=DIA
29 TTT(J)=TW(J)
30 CALL HCOEFF (T(J),TTT(J),PDATA(1),XL,H(J),PRAM(J),ZCONST,HMULT,HEX
1P,XMOLEC)
31 CONTINUE
C
C STEP-3-
C COMPUTE INITIAL VALUES OF QOUT, QIN, P AND DPDT
C
QOUT=QOUTD(1)
QIN =-CIND(1)
P=PDATA(1)
PHOLD=P
IF (MPCATA-1) 1,32,33
32 PP=P
    GO TO 34
33 CALL INTERP (PDATA,TIME2,MPDATA,TIME,PP)
34 DPDT=(PP-P)/DT
    IF (QOOO - 0. )144,144,42
42 DO 43 J=1,N
    CALL INTERP (TWBK,DIST7,MTBAK,X(J),TWB(J))
    CALL INTERP (TWCU,DIST8,MTCU,X(J),TWC(J))
    CALL INTERP (TSTN,DIST9,MTSS,X(J),TST(J))
    CALL INTERP (TWAL,DIS11,MTAL,X(J),TALS(J))
144 CONTINUE
C
C STEP-4-
C COMPUTE INITIAL VALUES OF COMPRESSIBILITY FACTOR AND DERIVATIVES
C
IF (ZCONST) 1,37,35
35 DO 36 J=1,150
    Z(J)=1.0
    Z1(J)=1.0
36 Z2(J)=1.0
    ZHOLD=1.0
    GO TO 39
C
37 DO 38 J=1,N
38 CALL CCMPRS (T(J),PDATA(1),Z(J),Z1(J),Z2(J),XMOLEC)
39 CONTINUE
C
C STEP-5-
C COMPUTE INITIAL VALUES OF LOCAL ULLAGE GAS VELOCITY
PX = PCATA(1)
C

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```

V(N)=FLOW(1)/AREA(N)
NTEMP=N-1
DO 40 L=1,NTEMP
J=N-L
C10=((H(J+1)+H(J))*(Z1(J+1)+Z1(J)))/(PX*(RAD(J+1)+RAD(J))*(CP(J+1)
1+CP(J)))
C11 = SQRT(1.0+((DRDX(J+1) + DRDX(J))/2.0)**2)
C12=DX*((DRDX(J+1)+DRDX(J))/(RAD(J+1)+RAD(J)))
C13=((Z1(J+1)**2+Z1(J)**2)/(XJAY*PX*(Z(J+1)+Z(J))*(CP(J+1)+CP(J)))
1)
C14=(Z2(J+1)+Z2(J))/((Z(J+1)+Z(J))*PX)
C15=((Z1(J+1)+Z1(J))*(2.0*QIN)/((AREA(J+1)+AREA(J))*PX*(CP(J+1)+CP
1(J))))
40 V(J)= 1./(1.-C12)*((1.+C12)*V(J+1)-C3*C10*(TW(J+1)+TW(J)-T(J+1)
1 - T(J))*C11 -(2.*C3*C13 - DX*C14)*DPDT - C3*C15)
C
C STEP-6-
C FIND GAS IN ULLAGE AT TIME ZERO BY INTEGRATING DENSITY
C
C
GASA=(.5*AREA(1)/(T(1)*Z(1))+(.5*AREA(N))/(T(N)*Z(N)))
NTEMP=N-1
DO 41 J=2,NTEMP
41 GASA=GASA+AREA(J)/T(J)/Z(J)
GASA=GASA*C4*P
GSTART=GASA
C
C STEP-7-
C WRITE PROBLEM IDENTIFICATION AND INPUT DATA
C
C
WRITE (6.1022) DT
C
C
IF(UNUMS)250,251,250
250 CONTINUE
GSTART = GSTART * .45359237
WRITE (6.2015) GSTART
GSTART = GSTART/.45359237
Q = Q * 1054.3503
WRITE (6.2050) Q
Q = Q/1054.3503
TNKWT = TNKWT * .45359237
WRITE (6.4000) TNKWT
GO TO 44
251 CONTINUE
WRITE (6.1015) GSTART
C
WRITE (6.1050 ) Q
WRITE (6.3000) TNKWT
C
QIN = QIND(1)
C *****
C

```

```

C          BEGIN MAIN PART OF CALCULATION
C
C          STEP-8-
C          FIND TEMPERATURES AT NEW TIME
C
44  CONTINUE
    CALL INTERP (TGAS,TIME1,MTGAS,TIME,TP(1))
    CALL INTERP (TSAT,TIME4,MTSAT,TIME,TP(N+1))
    CALL INTERP (TBULK,TIME5,MTBULK,TIME,TWP(N+1))
C
C
400  DO 48 J=2,N
      D1=C5(J)*DT*QOUT/CPW(J)
      D2=1.0+C5(J)*DT*H(J)/CPW(J)
      D3=D2/((C6/RAD(J))*H(J)*Z(J)*DT/P/CP(J))
      D3 = D3/SQRT(1.0+((DRDX(J+1)+DRDX(J))/2.))**2)
      D4=(C7*Z1(J)*DPDT+(C8/AREA(J))*Z(J)*(-QIN)+C8/X(N)*Z(J)/AREA(J)
      1*(-QTR))*DT/CP(J)/P
C
      BQUAD=D3*(1.0+V(J)*DT/DX-D4)-TW(J)-D1
      CQUAD=-D3*(T(J)+V(J)*DT/DX*TP(J-1))
      RX1 = -BQUAD/2.
      DISC = RX1*RX1 - CQUAD
      IF(DISC)45,45,46
45    ROOT1= 0.5 * (T(J) + TP(J-1))
      TP(J) = ROOT1
      GO TO 47
46    RX2 = SQRT(DISC)
      ROOT1 = RX1 + RX2
      IF(ROOT1)450,450,460
450  TP(J) = 0.5 * (T(J) + TP(J-1))
      GO TO 47
460  TP(J) = ROOT1
C
47    TWP(J)=(TW(J)+(D2-1.)*TP(J)+D1)/D2
48    CONTINUE
      DO 49 J=2,N
        D1=C5(J)*DT*QOUT/CPW(J)
        D2=1.0+C5(J)*DT*H(J)/CPW(J)
49    CONTINUE
C    SPECIFIC HEAT OPTION FOLLOWING STATEMENTS 51,52 IS USED WHEN THE
C    TANK LID IS (18-8) STAINLESS STEEL. THE EQUIVALENT THICKNESS
C    FOR THE LID MASS IS CONCENTRATED IN THE FIRST VOLUME ELEMENT.
      IF(SPWSS - 499.0)53,50,50
50    IF(TW(1) - 75.0)125,51,51
125  CPW(1) = 0.010
      GO TO 53
51    IF(TW(1) .GT. 220.)GO TO 52
      CPW(1)= 0.000418* TW(1) - 0.0203
      GO TO 53
52    W = (TW(1) - 220.)/126.67
      CPW(1) = ((0.0018 * W - 0.0127)*W + 0.0374)*W + 0.071
53    C5(1)=1.0/(TICK(1)*SPWSS)
      C9(1)=XPI*DX*DIA*TICK(1)*SPWSS
      D1=C5(1)*DT*QOUT/CPW(1)
      D2=1.0+C5(1)*DT*H(1)/CPW(1)

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      TWP(1)=(TW(1)+(D2-1.0)*TP(1)+D1)/D2
C
      CALL INTERP (QOOUT,TIME6,MQOUT,TIME,QOOUT)
      CALL INTERP (QIND,TIME7,MQIN,TIME,QIN)
      GO TO 54
C
54      IF (MPCDATA-1) 1.56,55
55      PHCLD=P
      CALL INTERP (PDATA,TIME2,MPCDATA,TIME,P)
      TIMEP=TIME+DT
      CALL INTERP (PDATA,TIME2,MPDATA,TIMEP,PP)
      DPDT=(PP-P)/DT
C
56      CONTINUE
C
C
      IF (QOQQ) 73,73,57
57      CONTINUE
      IF(AB .EQ. 0.) GO TO 122
C
C          STEP-9-
C          EVALUATE ENERGY TRANSFER TO INTERNAL HARDWARE
C
C      NOTE- CP-SPECF HEAT, BK-PHENOLIC, CU-COPPER, ST-STAINLESS, AL-ALUM
C      PHENOLIC SPECIFIC HEAT DATA ESTIMATED FROM TPRC PUB. VOL 6 PT. II
C      (THERMOPHYSICAL PROPERTIES RESEARCH CENTER-PURDUE UNIV.)
      DO 60 J=1,N
      IF(TP(J) - TWB(J))58,58,152
58      TB(J) = TP(J)
      GO TO 60
152      CPBK(J) = 0.000664 * TwB(J)
59      TTT(J)=TWB(J)
      CALL HCOEFF (T(J),TTT(J),P,XL,H(J),PRAM(J),ZCONST,HMULT,HEXP,XMOLE
1C)
      TB(J)=H(J)*AB*(T(J)-TWB(J))/(WTB*CPBK(J))*DT+TwB(J)
      DQ1=DQ1+H(J)*AB*(T(J)-TWB(J))*DT
60      CONTINUE
122      IF(A1C .EQ. 0.) GO TO 123
C      CURVE FIT-COPPER SPECIFIC HEAT DATA FROM WADD TECH REPT 60-56 1960
      DO 63 J=1,N
      IF(TP(J) - TWC(J))61,61,151
61      TC(J) = TP(J)
      GO TO 63
151      W = (TWC(J) - 25.0)/125.
      CPCU(J) = ((0.0021*W - 0.02)*W + 0.06683) *W
62      TTT(J)=TWC(J)
      CALL HCOEFF (T(J),TTT(J),P,XL,H(J),PRAM(J),ZCONST,HMULT,HEXP,XMOLE
1C)
      TC(J)=H(J)*A1C*(T(J)-TWC(J))/(WT1C*CPCU(J))*DT+TWC(J)
      DQ2=DQ2+H(J)*A1C*(T(J)-TWC(J))*DT
63      CONTINUE
123      IF(A3S .EQ. 0.) GO TO 124
C      CURVE FIT (18-8) STAINLESS STEEL SP HEAT FROM SCOTT CRYO ENGR. -
C      D. VAN. NOSTRAND
      DO 66 J=1,N

```

```

      IF(TP(J) - TST(J))64,64,135
135  IF(TST(J) - 75.)130,131,131
130  CPST(J) = 0.01
      GO TO 65
131  IF(TST(J) .GT. 220.0)GO TO 133
      CPST(J) = 0.000418 * TST(J) - 0.0203
      GO TO 65
133  W = (TST(J) - 220.)/126.67
      CPST(J) = ((0.0018*W-0.0127)*W + 0.0374)*W + 0.071
64   TZ(J) = TP(J)
      GO TO 66
65   TTT(J)=TST(J)
      CALL HCOEFF (T(J),TTT(J),P,XL,H(J),PRAM(J),ZCONST,HMULT,HEXP,XMOLE
1C)
      TZ(J)=H(J)*A3S*(T(J)-TST(J))/(WT3S*CPST(J))*DT+TST(J)
      DQ3=DQ3+H(J)*A3S*(T(J)-TST(J))*DT
66   CONTINUE
124  IF(A58 .EQ. 0.) GO TO 126
C    CURVE FIT OF AL. ALLOY 6061-T6 SPECIFIC HEAT DATA FROM TPRC
      DO 72 J=1,N
      IF(TP(J) - TALS(J))70,70,153
70   TBC(J) = TP(J)
      GO TO 72
153  IF(TALS(J) - 70.0)67,68,68
67   CPAL(J) = 0.000397 * TALS(J) - 0.013
      IF(TALS(J) .LT. 36.0)CPAL(J)=0.0012
      GO TO 69
68   W = (TALS(J) - 70.)/117.5
      CPAL(J) = ((0.00334*W - 0.0351)*W + 0.13666)*W + 0.015
      IF(TALS(J) .GT. 540.) CPAL(J) = 0.212
69   CONTINUE
71   TTT(J)=TALS(J)
      CALL HCOEFF (T(J),TTT(J),P,XL,H(J),PRAM(J),ZCONST,HMULT,HEXP,XMOLE
1C)
      TBC(J)=H(J)*A5B*(T(J)-TALS(J))/(WT5B*CPAL(J))*DT+TALS(J)
      DQ4=DQ4+H(J)*A5B*(T(J)-TALS(J))*DT
72   CONTINUE
126  QIN = (DQ1 + DQ2 + DQ3 + DQ4)/ (TIME * X(N))
73   CONTINUE
C
C           STEP-10-
C           FIND COMPRESSIBILITY FACTORS AT NEW TIME
C
      IF (ZCONST) 1,74,76
74   ZHOLD=Z(5)
      DO 200 K=1,N
200  ZAV(K) = Z(K)
      DO 75 J=1,NP
75   CALL CCMPRS (TP(J),P,Z(J),Z1(J),Z2(J),XMOLEC)
76   CONTINUE
C
C

```



```

C          STEP-11-
C          FIND VELOCITIES AT NEW TIME
C
VHOLD=V(5)
CALL INTERP (FLOW,TIME3,MFLOW,TIME,FLOWNP)
V(NP) = FLOWNP/AREA(NP)
C
DO 77 J=1,N
K=NP-J
77 V(K) = (TP(K)*V(K+1)-(DX/(DT*Z(K)))*(Z1(K)*(TP(K)-T(K))
1 + Z2(K)*TP(K)*DPDT*DX/(Z(K)*PP))/(TP(K)+(Z1(K)/Z(K))*(TP(K+1)
2 - TP(K)) - (2.0*DX *TP(K) * (DRDX(K+1)+DRDX(K)))/(RAD(K+1)
3 + RAD(K)))
C
C          STEP-12-
C          FIND HEAT FLOW RATE TO WALL AND TOTAL HEAT ADDED TO WALL
C
DQ=C9(1)*CPW(1)*(TWP(1)-TW(1))
DO 78 J=2,N
78 DQ=DQ+RAD(J)*SQRT(1.0+DRDX(J)**2)*CPW(J)*(TWP(J)-TW(J))*C9(J)
Q=Q+DQ
C
C          FIND GAS FLOW RATE AND TOTAL GAS ADDED UP TO THE NEW TIME
GASB=0.5*AREA(1)/TP(1)/Z(1)+0.5*AREA(NP)/TP(NP)/Z(NP)
DO 79 J=2,N
79 GASB=GASB+AREA(J)/TP(J)/Z(J)
GASB=GASB*C4*P
C
C          NOTE GASCHECK CALCULATION BASED ON CROSS SECTION AT NET POINT =5
C
GSRATE=ABS((GASB-GASA)/DT)
GAS=GASB-GSTART
GASCHK=GASCHK+0.25*(V(5)+VHOLD)/(C8/AREA(5))*DT*(PHOLD/ZHOLD/T(5)+
1P/Z(5)/TP(5))
C
C          STEP-13-
C          FIND SPECIFIC HEATS AT NEW TIME
C
DO 80 J=1,NP
80 CALL SPHEAT (TP(J),TWP(J),CP(J),CPW(J),XMOLEC)
C
C          STEP-14-
C          FIND HEAT TRANSFER COEFFICIENT AT NEW TIME
C
IF(TADD)82,82,81
81 XL=2.0*RAD(N+1)
TTT(N+1)=TP(N+1)
CALL HCOEFF (TADD,TTT(N+1),P,XL,H(N+1),PRAM(N+1),ZCONST,HMULT,HEXP
1,XMOLEC)
H2H=H(N+1)
300 HSUR = H2H * .14/HMULT
QTR=HSUR*AREA(N+1)*(TADD-TP(N+1))
CQTR=CQTR+QTR*DT
GO TO 83
82 QTR=0.0
83 IF (HCCNST) 1,84,89
84 CONTINUE

```



```
C
C                                     STEP-16-
C      END TIME EXCEEDED - INTERPOLATE CONDITIONS AT END TIME
C
98    RATIO=(ENDTIM-TIME+DT)/DT
      TIME=ENDTIM
C
      DO 99 J=1,N
      TP(J)=T(J)+RATIO*(TP(J)-T(J))
99    TWP(J)=TW(J)+RATIO*(TWP(J)-TW(J))
C
      Q=C-DG+RATIO*DQ
      GAS=GAS-GASB+GASA+RATIO*(GASB-GASA)
      GASCHK=GASCHK-GASB+GASA+RATIO*(GASB-GASA)
      X(NP)=X(N)+RATIO*DX
C
C                                     STEP-17-
C      WRITE OUT RESULTS REFER TO SUBROUTINE WRITE 2
      CALL WRITE2
C
      GO TO 1
C
C
C      *****
C
C      FORMAT STATEMENTS
C
100   FORMAT (1H1,30X,24H  TANK EXPULSION PROGRAM/1HJ)
101   FORMAT (80H
1     )
102   FORMAT (8F10.0)
103   FORMAT (F10.0)
1015  FORMAT (1HK,23H  INITIAL ULLAGE GAS = F6.3,5H  LBS)
1022  FORMAT (1HK, 27H  INITIAL TIME INCREMENT = F6.1,9H  SECONDS)
1050  FORMAT (1HK, 25H  INITIAL HEAT TO WALL = F7.1, 5H  BTU)
2015  FORMAT (1HK,23H  INITIAL ULLAGE GAS = F6.3,10H KILOGRAM)
2050  FORMAT (1HK, 25H  INITIAL HEAT TO WALL = E11.4, 7H  JOULE)
3000  FORMAT (1HK, 29H  THE TANK WEIGHT LESS LID = F7.1, 5H  LBS)
4000  FORMAT (1HK, 29H  THE TANK WEIGHT LESS LID = F7.2,10H KILOGRAM)
      END
```

## TANK EXPULSION PROGRAM

TEST CASE TO EXAMINE THE HARDWARE OPTION USING SI UNITS  
CYLINDRICAL TEST SECTION - CIRCUMFERENTIAL ALUM. BAFFLES  
100 SECCND EXPULSION - 0.61 METER TANK RADIUS

\$OTPNIS

MTGAS =	1, MPDATA=	1, MFLOW =	1, MTSAT =	1, MTBULK=	1,
MQUOT =	0, MQIN =	0, MTWIN =	2, MTGIN =	2, MRAD =	2,
MTICK =	2, MTBAK =	0, MTCU =	0, MTSS =	0, MTAL =	2,
\$ ENC					

## INPUT DATA

INITIAL NUMBER OF NETPOINTS = 15.  
INITIAL ULLAGE = 0.325 METER  
TANK RADIUS = 0. METER  
TANK WALL SPECIFIC WEIGHT = 2803.2 KG/CUBIC METER  
MOLECULAR WEIGHT = 2.0

GAS TEMP, DEG K VS TIME, SECONDS

277.8 0.

PRESSURE, N-NEWTON/SQ M VS TIME, SECONDS

0.7 0.

FLOW RATE, CU M/SEC VS TIME, SECONDS

0.0285 0.

SATURATION TEMP, DEG K VS TIME, SECONDS

25.2 0.

PULK TEMP, DEG K VS TIME, SECONDS

20.3 0.

OUTSIDE HEATING RATE, JOULE/SQ M-SEC VS TIME, SECONDS

0. 0.

INSIDE HEATING RATE, JOULE/METER-SEC VS TIME, SECONDS

0. 0.

# INITIAL TEMPERATURE-DEG. KELVIN

X COORDINATE	WALL TEMPERATURE	GAS TEMPERATURE
0.	55.6	163.9
0.02	53.1	154.3
0.05	50.6	144.7
0.07	48.1	135.0
0.09	45.6	125.4
0.12	43.2	115.8
0.14	40.7	106.2
0.16	38.2	96.6
0.19	35.7	86.9
0.21	33.2	77.3
0.23	30.8	67.7
0.26	28.3	58.1
0.28	25.8	48.5
0.30	23.3	38.8
0.32	20.8	29.2

HEAT TRANSFER COEFFICIENT WILL BE COMPUTED  
FMULT = 0. FEXP = 0.

## TANK RADIUS (METER) VS AXIAL DISTANCE (METER)

0.610	0.
0.610	3.25

A REAL GAS IS ASSUMED

THE PRESSURANT IS HYDROGEN

INITIAL TIME INCREMENT = 1.0 SECONDS

INITIAL ILLAGE GAS = 0.887 KILOGRAM

INITIAL HEAT TO WALL = 0. JOULE

THE TANK WEIGHT LFSS LID = 1.60 KILOGRAM

TIME =	5.5	SECONDS	GAS SUPPLIED = 0.1614 KILOGRAM		HEAT TO WALL = 0.1175E+05 JOULE		INLET VEL = 0.0258 METER/SEC	
PLAT TOLIC =	0.	J	CHUCK ON GAS = 0.22+ KG		GAS FLOW = 0.0181 KG/SEC		HEAT TO HARD = 0.3053E+04 J/(M-SEC)	
X, METER	WALL TEMP-K	GAS TEMP-K	X, METER	WALL TEMP-K	GAS TEMP-K	X, METER	WALL TEMP-K	GAS TEMP-K
0.	272.2	277.8	0.0232	266.8	277.2	0.0464	261.0	275.9
0.055	253.8	273.1	0.0928	244.7	268.2	0.1160	234.0	260.6
0.1353	221.7	250.4	0.1625	208.4	237.8	0.1857	194.4	223.5
0.2089	190.2	208.3	0.2321	166.2	192.7	0.2553	152.4	177.4
0.2795	159.4	162.6	0.3017	127.4	148.5	0.3249	116.5	135.2
0.3481	127.0	122.6	0.3713	94.1	110.7	0.3545	85.9	59.4
0.4178	85.7	88.5	0.4410	72.0	78.1	0.4642	63.4	68.0
0.4874	55.1	59.1	0.5106	46.3	48.4	0.5338	38.6	38.8
0.5570	29.9	29.2						

TIME = 19.0 SECONDS  
 GAS SUPPLIED = 0.3356 KILOGRAM HEAT TO WALL = 0.2552E+05 JOULE INLET VEL = 0.0262 METER/SEC  
 HEAT TO LIQ = 0.  
 J CHECK ON GAS = 0.399 KG GAS FLOW = 0.0184 KG/SEC HEAT TO HARD = 0.202E+04 J/(M-SEC)  
 X, METER WALL TEMP-K GAS TEMP-K X, METER WALL TEMP-K GAS TEMP-K X, METER WALL TEMP-K GAS TEMP-K

0.	276.4	277.8	0.0232	275.4	277.6	0.0464	274.4	277.4
0.0656	273.4	277.1	0.0928	272.1	276.8	0.1160	270.5	276.4
0.1353	268.5	275.9	0.1625	266.0	275.1	0.1857	262.8	273.9
0.2089	253.8	272.2	0.2321	254.0	269.6	0.2553	248.2	266.1
0.2785	241.4	261.4	0.3017	233.7	255.4	0.3249	225.0	248.1
0.3481	215.5	239.5	0.3713	205.2	229.8	0.3945	194.5	219.0
0.4178	183.2	207.5	0.4410	171.8	195.4	0.4642	160.2	183.0
0.4874	148.5	170.5	0.5106	137.2	158.1	0.5328	126.3	145.9
0.5570	116.2	134.0	0.5802	107.2	122.4	0.6034	99.5	111.1
0.6266	90.5	100.2	0.6498	81.6	89.5	0.6730	72.8	79.1
0.6963	64.2	68.9	0.7195	55.7	58.9	0.7427	46.7	48.9
0.7659	38.5	39.1	0.7891	20.8	29.2			

TIME = 28.6 SECONDS  
 GAS SUPPLIED = 0.5132 KILOGRAM HEAT TO WALL = 0.3578E+05 JOULE INLET VEL = 0.0265 METER/SEC  
 HEAT TO LIQ = 0.  
 J CHECK ON GAS = 0.576 KG GAS FLOW = 0.0187 KG/SEC HEAT TO HARD = 0.1521E+04 J/(M-SEC)  
 X, METER WALL TEMP-K GAS TEMP-K X, METER WALL TEMP-K GAS TEMP-K X, METER WALL TEMP-K GAS TEMP-K

0.	277.2	277.8	0.0232	276.8	277.6	0.0464	276.5	277.5
0.0656	276.1	277.3	0.0928	275.7	277.2	0.1160	275.3	277.0
0.1353	274.8	276.8	0.1625	274.2	276.6	0.1857	273.6	276.4
0.2089	272.8	276.2	0.2321	271.9	275.9	0.2553	270.7	275.5
0.2785	269.4	275.1	0.3017	267.7	274.5	0.3249	265.7	273.7
0.3481	263.3	272.7	0.3713	260.4	271.3	0.3945	256.9	269.4
0.4178	252.8	267.0	0.4410	248.1	263.9	0.4642	242.6	260.0
0.4874	236.5	255.3	0.5106	229.7	249.7	0.5328	222.2	243.2
0.5570	214.1	235.7	0.5802	205.3	227.4	0.6034	196.1	218.4
0.6266	186.4	208.6	0.6498	176.4	198.3	0.6730	166.2	187.7
0.6963	155.7	176.7	0.7195	145.2	165.6	0.7427	134.8	154.4
0.7659	124.8	143.3	0.7891	115.3	132.3	0.8123	106.7	121.4
0.8355	99.3	110.7	0.8587	90.6	100.1	0.8819	81.8	89.7
0.9051	73.0	79.4	0.9283	64.5	69.2	0.9515	56.0	59.2
0.9748	46.9	49.2	0.9980	39.0	39.2	1.0212	20.8	29.2

TIME = 100.0 SECONDS		GAS SUPPLIED = 1.8690 KILOGRAM		HEAT TO WALL = 0.1507E+06 JOULE		INLET VLL = J.C266 METER/SEC			
HEAT TO LIC = 0.		J		CHECK ON GAS = 1.024 KJ		GAS FLOW = 0.0189 KG/SEC		HEAT TO HARD = 0.5568E+03 J/(M-SEC)	
X, METER	WALL TEMP-K	GAS TEMP-K	X, METER	WALL TEMP-K	GAS TEMP-K	X, METER	WALL TEMP-K	GAS TEMP-K	GAS TEMP-K
0.	277.8	277.8	0.0232	277.7	277.7	0.0464	277.7	277.7	277.7
0.0696	277.6	277.6	0.0928	277.5	277.5	0.1160	277.5	277.5	277.5
0.1393	277.4	277.5	0.1625	277.4	277.4	0.1857	277.3	277.3	277.4
0.2084	277.2	277.3	0.2321	277.2	277.2	0.2553	277.1	277.1	277.2
0.2785	277.1	277.2	0.3017	277.0	277.0	0.3245	276.9	276.9	277.0
0.3481	276.9	277.0	0.3713	276.8	276.8	0.3945	276.7	276.7	276.9
0.4178	276.7	276.8	0.4410	276.6	276.6	0.4642	276.5	276.5	276.7
0.4874	276.4	276.6	0.5106	276.4	276.4	0.5338	276.3	276.3	276.5
0.5570	276.2	276.5	0.5802	276.2	276.4	0.6034	276.1	276.3	276.3
0.6266	276.0	276.3	0.6498	275.9	276.2	0.6720	275.8	276.1	276.3
0.6963	275.8	276.1	0.7195	275.7	276.0	0.7427	275.6	275.9	276.1
0.7659	275.5	275.9	0.7891	275.4	275.8	0.8123	275.3	275.7	275.9
0.8355	275.3	275.7	0.8587	275.2	275.6	0.8819	275.1	275.5	275.7
0.9051	275.0	275.4	0.9283	274.9	275.4	0.9515	274.8	275.3	275.5
0.9748	274.7	275.2	0.9980	274.6	275.1	1.0212	274.5	275.1	275.3
1.0444	274.4	275.0	1.0676	274.3	274.9	1.0908	274.2	274.8	275.1
1.1140	274.0	274.7	1.1372	273.9	274.6	1.1604	273.8	274.6	274.8
1.1836	273.7	274.5	1.2068	273.5	274.4	1.2300	273.4	274.3	274.6
1.2533	273.2	274.2	1.2765	273.1	274.1	1.2997	272.9	274.0	274.3
1.3229	272.7	273.9	1.3461	272.6	273.8	1.3693	272.3	273.6	273.6
1.3925	272.1	273.5	1.4157	271.9	273.4	1.4385	271.6	273.3	273.6
1.4621	271.4	273.1	1.4853	271.1	273.0	1.5085	270.7	272.8	273.3
1.5318	270.4	272.6	1.5550	270.0	272.4	1.5782	269.5	272.2	272.8
1.6014	269.0	271.9	1.6246	268.5	271.6	1.6478	267.9	271.3	272.2
1.6710	267.2	271.0	1.6942	266.5	270.6	1.7174	265.6	270.1	271.3
1.7406	264.7	269.6	1.7638	263.6	269.0	1.7870	262.5	268.3	270.1
1.8103	261.2	267.5	1.8335	259.7	266.6	1.8567	258.1	265.5	268.3
1.8799	256.3	264.3	1.9031	254.4	263.0	1.9263	252.2	261.4	265.5
1.9495	249.8	259.7	1.9727	247.2	257.7	1.9959	244.3	255.5	261.4
2.0191	241.2	253.1	2.0425	237.9	250.4	2.0655	234.3	247.3	255.5
2.0988	230.4	244.0	2.1120	226.2	240.3	2.1352	221.7	236.4	247.3
2.1584	216.5	232.0	2.1816	211.8	227.3	2.2048	206.4	222.3	236.4
2.2280	200.7	216.9	2.2512	194.7	211.1	2.2744	188.5	205.0	222.3
2.2976	181.9	198.6	2.3203	175.1	191.8	2.3440	168.1	184.7	205.0
2.3673	160.7	177.4	2.3905	153.1	169.7	2.4137	145.3	161.9	184.7
2.4369	137.4	153.8	2.4601	129.5	145.5	2.4823	121.6	137.1	161.9
2.5065	113.9	129.5	2.5297	106.7	119.9	2.5525	100.2	111.1	137.1
2.5761	93.1	102.2	2.5993	85.4	93.2	2.6225	77.5	84.2	111.1
2.6458	69.8	75.2	2.6690	62.0	66.1	2.6922	54.1	56.9	84.2
2.7154	46.5	47.8	2.7386	38.4	38.6	2.7618	21.4	29.5	56.9
2.7626	20.8	29.2							29.5

# APPENDIX C

## LISTING OF RAMP PROGRAM

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C
C      THIS IS THE PRESSURIZATION MAIN PROGRAM
C      *****
C      DIMENSION TGAS(100), TIME1(100), PDATA(100), TIME2(100), FLOW(25),
1 TIME3(25), TSAT(50), TIME4(50), TBULK(25), TIME5(25), QOUTD(25),
2 TIME6(25), QIND(25), TIME7(25), ZAV(250), TWIND(100), DIST1(100),
3 TGIND(100), DIST2(100), X(250), T(250), TP(250), TW(250), TWP(250)
4, V(250), VP(250), CP(250), CPW(250), H(250), Z(250), Z1(250), Z2(
5250), RAD(250), AREA(250), YRAD(250), XRAD(250), DRCX(250), TEST(2
650)
C
C      DIMENSION C5(250), C9(250), YTICK(250), XXT(250), TICK(250), XR(3)
1, AQ(3)
C      COMMON X,T,TP,TW,TWP,V,CP,CPW,TGAS,TIME1,MTGAS,PDATA,TIME2,MPDATA,
1FLOW,TIME3,MFLOW,TSAT,TIME4,MTSAT,TBULK,TIME5,MTBULK,QOUTD,TIME6,M
2QOUT,QIND,TIME7,MQIN,N,NP,XN,ULLAGE,RADIUS,TLID,SPWGT,XMOLEC,GSTAR
3T,HCONST,TIME,GAS,Q,GASCHK,GSRATE,DT,ZCONST,I,HMULT,HEXP,YRAD,XRAD
4,MRAD,DQ,QIN,UNUMS,TWIND,DIST1,MTWIN,TGIND,DIST2,MTGIN,DIA,
5TADC,YTICK,XXT,MTICK
C
C      *****
C
C      READ 3 CARDS OF PROBLEM DESCRIPTION AND WRITE OUT. THERE
C      MUST BE THREE CARDS USED, ALTHOUGH ANY OR ALL OF THEM MAY
C      BE BLANK. LEAVE THE FIRST COLUMN OF EACH CARD BLANK AND
C      ENTER ANY INFORMATION IN COLUMNS 2 TO 80.
C
1  WRITE (6,106)
   DO 2 J=1,3
   READ (5,107)
2  WRITE (6,107)
C
C      THIS IS THE PRESSURIZATION PROGRAM
C
C      NOMENCLATURE FOR INPUT DATA
C
C      XN,          NUMBER OF NETPOINTS AT TIME ZERO (MUST BE 3.0 OR MORE)
C      QUTPUT,      NUMBER OF TIME STEPS TAKEN BEFORE EACH OUTPUT
C      ULLAGE,      INITIAL ULLAGE LENGTH, FEET (CANNOT BE ZERO)
C      RADIUS,      TANK RADIUS, - SPECIFY WHEN TANK IS A CYLINDER
C                  THE PROGRAM THEN ASSUMES SPHERICAL END SECTIONS.
C                  IF RADIUS = 0., THE RADIUS IS INTERPOLATED BASED ON THE
C                  TANK RADIUS (VS DISTANCE FROM TOP) DATA READ INTO THE
C                  PROGRAM. IF RADIUS = -1, THE TANK IS A SPHERE.
C      SPWGT,       TANK WALL SPECIFIC WEIGHT
C      SPWSS,       SPECIFIC WEIGHT OF TANK LID MATERIAL
C      ENDTIM,      TIME TO COMPLETE THE HOLD PERIOD
C      XMOLEC,      MOLECULAR WEIGHT OF PRESSURIZING GAS
C      ZCONST,      COMPRESSIBILITY FACTOR (1. FOR IDEAL GAS, BLANK FOR REAL)

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C      HCONST,    HEAT TRANSFER COEFF. (BLANK IF H IS TO BE CALCULATED)
C                  BTU/HR./SQ.FT./DEG.F., WATTS/SQ. M/DEG K
C      DT,        INITIAL TIME STEP (SECONDS)
C      ENDRMP,    TIME TO COMPLETE THE RAMP PERIOD (SECONDS)
C      DIA,       DIAMETER WHEN THE TANK IS A SPHERE, OR CYLINDER.
C                  SPECIFY DIAMETER ON VERTICAL AXIS WHEN TANK IS SPHEROID
C      P1,P2,     TIME COORDINATES(SECONDS) ALONG THE PRESSURE RISE CURVE
C      P3,P4,     THESE CONTROL THE INITIAL SELECTION OF THE TIME STEP
C                  SEE EFN STATEMENT 96 ET CETERA FOR SIGNIFICANCE
C      CYLN,      WHEN RADIUS IS SPECIFIED, THE CYLINDRICAL LENGTH BETWEEN
C                  THE TANK END SECTIONS MUST BE DEFINED.
C
C                  IF HCONST IS BLANK H WILL BE COMPUTED FROM THE EQUATION
C                   $H = HMULT*COND/XL*(NUSSELT*PRANDTL)**HEXP$ 
C
C      HMULT,     CONSTANT IN ABOVE EQUATION (0.13 IS USED IF LEFT BLANK)
C      HEXP,      CONSTANT IN ABOVE EQUATION (0.333 IS USED IF LEFT BLANK)
C      TLID       THE MASS OF THE TANK LID AND FLANGE MADE EQUIVALENT
C                  TO THE FIRST WALL THICKNESS
C      UNUMS,     SPECIFY GREATER THAN 0. TO PROGRAM IN SI UNITS
C
C      GROUP I DATA  RAMP DATA
C      *****
C      NAMELIST / PARAMS / XN,OUTPUT,ULLAGE,RADIUS,SPWGT,ENDTIM,XMOLEC,
C      1HCONST,DIA,ZCONST,HMULT,HEXP,SPWSS,DT,ENDRMP,PM1,PM2,PM3,PM4,CYLN,
C      2UNUMS
C      READ (5,PARAMS)
C
C      GROUP II DATA  RAMP DATA CONTINUED
C      *****
C      NAMELIST / INPNTS / MTGAS,MPDATA,MFLOW,MTSAT,MTBULK,MQOUT,MQIN,
C      1MTWIN,MTGIN,MRAD,MTICK
C      READ (5,INPNTS)
C      NAMELIST / OTPNTS / MTGAS,MPDATA,MFLOW,MTSAT,MTBULK,MQOUT,MQIN,
C      1MTWIN,MTGIN,MRAD,MTICK
C      WRITE (6,OTPNTS)
C      NAMELIST / TABLES /
C      1 TGAS , TIME1 , PDATA , TIME2 , FLOW , TIME3 ,
C      2 TSAT , TIME4 , TBULK , TIME5 , QOUTD , TIME6 ,
C      3 QIND , TIME7 , TWIND , DIST1 , TGINO , DIST2 ,
C      4 YRAD , XRAD , YTICK , XXT
C      READ (5,TABLES)
C      *****
C
C      PRELIMINARY COMPUTATION
C
C      GSTART=0.0
C      TIMY=0.0
C      LOOM=0
C      ITER1=0
C      Q=0.
C      GASCHK=0.
C      TICK(1)=YTICK(1)
C      TLID=TICK(1)
C      CALL WRITE1

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```

C      IF (UNUMS .EQ. 0.) GO TO 301
      CALL SINTS
301    CONTINUE
      TPP=1.
      XPI=3.14159
      R=1545.4
      XJAY=778.2
      HCONST=HCONST/3600.

C      N=XN
      NP=N+1
      DX=ULLAGE/(XN-1.0)
      IWRITE=OUTPUT
      CHECK=FLOW(1)
      DETY=DT

C      C8=R/XMOLEC
      C3=DX*C8
      C1=C3/2.
      C2=C1/XJAY
      C4=DX/C8
      C6=2.*C8
      C7=C8/XJAY
      UWTP = 2.0*XPI*DX*SPWGT
      DO 3 J=2,250
      XJTICK=J-1
      X(J)=DX*XJTICK
      CALL INTERP (YTICK,XXT,MTICK,X(J),TICK(J))
      C5(J)=1.0/(TICK(J)*SPWGT)
3      C9(J) = UWTP * TICK(J)
      X(1)=0.

C
C      STEP- 1A-
C      MAKE GEOMETRY CALCULATIONS
C
      IF (RADIUS) 12,4,6
4      DO 5 J=2,250
      XJTEMP=J-1
      CALL INTERP (YRAD,XRAD,MRAD,X(J),RAD(J))
5      AREA(J)=XPI*RAD(J)**2
      RAD(1)=RAD(2)
      AREA(1)=AREA(2)
      GO TO 16
6      CONTINUE
      DO 10 J=2,250
      IF (X(J)-DIA/2.) 7,8,8
7      RAD(J)=SQRT(DIA*X(J)-X(J)**2)
      AREA(J)=XPI*RAD(J)**2
      GO TO 10
8      IF (X(J).GT.(CYLN+RADIUS)) GO TO 9
      RAD(J)=RADIUS
      AREA(J)=XPI*RAD(J)**2
      GO TO 10
9      PLEG=X(J)-CYLN-RADIUS

```

```

      IF (PLEG.GE.RADIUS) GO TO 11
      RAD(J)=SQRT(RADIUS**2-PLEG**2)
      AREA(J)=XPI*RAD(J)**2
10    CONTINUE
11    RAD(1)=RAD(2)
      AREA(1)=AREA(2)
      GO TO 16
C
12    DO 14 J=2,250
      XJTEMP=J-1
      IF (X(J)-DIA) 13,13,15
13    RAD(J)=SQRT(DIA*X(J)-X(J)**2)
14    AREA(J)=XPI*X(J)*(DIA-X(J))
15    AREA(1)=AREA(2)
      RAD(1)=RAD(2)
C
16    CONTINUE
C    THE NEXT 3 CARDS ARE SKIPPED SINCE THE FLOW DATA IS ZERO IN RAMP
C    DT=DX*AREA(N)/FLOW(1)
C    CALL INTERP(FLOW,TIME3,MFLOW,DT,FLO)
C    DT= DX* AREA(N)/(FLOW(1)+FLO)*2.0
      TIME=DT
C
C          STEP-1B-
C          COMPUTE INITIAL WALL AND GAS TEMPERATURES
C
      DO 17 J=1,N
      CALL INTERP (TWIND,DIST1,MTWIN,X(J),TW(J))
      CALL INTERP (TGIND,DIST2,MTGIN,X(J),T(J))
C
C          STEP -1C-
C          COMPUTE INITIAL VALUES OF SPECIFIC HEAT
C
17    CALL SPFEAT (T(J),TW(J),CP(J),CPW(J),XMOLEC)
C
C          STEP-2-
C          COMPUTE INITIAL VALUES OF HEAT TRANSFER CCEFFICIENT
C
      IF (HCONST) 1,20,18
C
18    DO 19 J=1,250
19    H(J)=HCONST
      GO TO 26
C
20    IF (HMULT) 1,21,22
21    HMULT=C.13
C
22    IF (HEXP) 1,23,24
23    HEXP=0.333
C
24    DO 25 J=1,N
      XL=ULLAGE+X(J)
25    CALL HCOEFF (T(J),TW(J),PDATA(1),XL,H(J),ZCONST,HMULT,HEXP,XMOLEC)
26    CONTINUE

```

```

C
C
C      STEP-3-
C      COMPUTE INITIAL VALUES OF COMPRESSIBILITY FACTOR AND
C      ITS DERIVATIVES
C
C      IF (ZCCNST) 1,29,27
C
27      DO 28 J=1,250
          Z(J)=1.0
          Z1(J)=1.0
28      Z2(J)=1.0
          ZHOLD=1.0
          GO TO 31
C
29      DO 30 J=1,N
30      CALL COMPRS (T(J),PDATA(1),Z(J),Z1(J),Z2(J),XMOLEC)
31      CONTINUE
C
C
C      STEP-4-
C      INITIALIZE VALUES FOR QOUT, QIN, P AND DPDT
C
          QOUT=QOUTD(1)
          QIN=-QIND(1)
          P=PDATA(1)
          PHOLD=P
C
          IF (MPDATA-1) 1,32,33
32      PP=P
          GO TO 34
C
33      CALL INTERP (PDATA,TIME2,MPDATA,TIME,PP)
34      DPDT=(PP-P)/DT
          DPOTP V=DPDT
C
          DO 35 J=2,N
35      DRDX(J)=(RAD(J+1)-RAD(J))/(X(J+1)-X(J))
          DRDX(N+1)=DRDX(N)
          DRDX(1)=(RAD(2)-RAD(1))/X(2)
C
C      STEP-5-
C
C      COMPUTE INITIAL VALUES OF LOCAL ULLAGE GAS VELOCITY
C
36      V(N)=FLOW(1)/AREA(N)
          NTEMP=N-1
          DO 37 L=1,NTEMP
              J=N-L
              C12=DX*((DRDX(J+1)+DRDX(J))/(RAD(J+1)+RAD(J)))
              C10=H(J)*Z1(J)/(P*RAD(J)*CP(J))
              C11=SQRT(1.0+((DRDX(J+1)+DRDX(J))/2.0)**2)
              VA=C3*C10*(TW(J)-T(J))*C11+(C1/AREA(J))*Z1(J)*QIN/P/CP(J)+(C2*Z1(J)
1) **2/CP(J)-.5*DX*Z2(J))*DPDT/P/Z(J)
              VA=VA/(1.0-C12)
              K=J+1

```

```

C20=F(K)*Z1(K)/(P*RAD(K)*CP(K))
VB=C3*C20*(TW(K)-T(K))*C11+(C1/AREA(K))*Z1(K)*QIN/P/CP(K)+(C2*Z1(K
1)**2/CP(K)-.5*DX*Z2(K))*DPDT/P/Z(K)
VB=VB/(1.0-C12)
37 V(J)=(1.0+C12)/(1.0-C12)*V(J+1)-VA-VB
WRITE (6,111)
WRITE (6,112) (V(J),J=1,N,10)
IF (GSTART.GT.0.) GO TO 40

C
C STEP-6-
C FIND GAS IN ULLAGE AT TIME ZERO BY INTEGRATING DENSITY
C
GASA=0.5*AREA(1)/T(1)/Z(1)+0.5*AREA(N)/T(N)/Z(N)
NTEMP=N-1
DO 38 J=2,NTEMP
38 GASA=GASA+AREA(J)/T(J)/Z(J)
GASA=GASA*C4*P
GSTART=GASA

C
C *****
C STEP-7-
C
C WRITE PROBLEM IDENTIFICATION AND INPUT DATA
C
C
IF(UNUMS)250,251,250
250 CONTINUE
GSTART = GSTART * .4535924
WRITE (6,2015) GSTART
GSTART = GSTART/.4535924
Q = Q * 1054.3503
WRITE (6,2050) Q
Q = Q/1054.3503
GO TO 120
251 CONTINUE
WRITE (6,1015) GSTART

C
WRITE (6,1050) Q

C
120 CONTINUE
C *****
C
C BEGIN MAIN PART OF CALCULATION
C
T(1)=TCAS(1)

C
C INITIALIZE AN ESTIMATE FOR TP(J)
C
NJ=N-1
DO 39 KI=1,N
39 TP(KI)=T(KI)
C

```

```

C          STEP-8-
C          FIND TEMPERATURES AT NEW TIME
C
40  CALL INTERP (TGAS,TIME1,MTGAS,TIME,TP(1))
    CALL INTERP (TSAT,TIME4,MTSAT,TIME,TP(N))
    CALL INTERP (TBULK,TIME5,MTBULK,TIME,TWP(N))
C
    KSTAR=C
    ZHOLD=Z(2)
    VHOLD=V(2)
C          FIND MISCELLANEOUS QUANTITIES AT NEW TIME
C
    CALL INTERP (QOUTD,TIME6,MQOUT,TIME,QOUT)
    CALL INTERP (QIND,TIME7,MQIN,TIME,QIN)
    QIN = -QIN
    IF (MPCATA-1) 1,42,41
41  PHOLD=P
    CALL INTERP (PDATA,TIME2,MPDATA,TIME,P)
    TIMEP=TIME+DT
    CALL INTERP (PDATA,TIME2,MPDATA,TIMEP,PP)
    DPDT=(P-PHOLD)/DT
C
42  CONTINUE
C
C          INITIALIZE AN ESTIMATE FOR VELOCITY
    DO 45 J=2,NJ
    IF (DPDTPV-0.) 43,43,44
43  V(J)=V(J)
    GO TO 45
44  V(J)=V(J)*DPDT/DPDTPV
45  CONTINUE
    DPDTPV=DPDT
C
    KLAMP=0
C
    ISTAR=C
46  CONTINUE
    DO 54 J=2,NJ
C
    D1=C5(J)*DT*QOUT/CPW(J)
    D2=1.0+C5(J)*DT*H(J)/CPW(J)
    D3=D2/((C6/RAD(J))*H(J)*Z(J)*DT/P/CP(J))
    D3=D3/SQRT(1.0+((DRDX(J+1)+DRDX(J))/2.))**2)
    D4=(C7*Z1(J)*DPDT+(C8/AREA(J))*Z(J)*QIN)*DT/CP(J)/P
    G1=D3-C3*D4-TW(J)-D1
    G2=C3*CT/DX
    G3=D3*T(J)
C
    G4=G1(J)/Z(J)*DX/DT
    G5=Z2(J)/Z(J)*DX*DPDT/P
C
    G6=G5-C4
    G7=G4*T(J)
    G8=1.0-Z1(J)/Z(J)-2.*DX/RAD(J)*DRDX(J)
C
    PHE=Z1(J)/Z(J)*TP(J+1)+G1*G8+G2*(V(J+1)+G6)

```

```

UU=G1*Z1(J)/Z(J)*TP(J+1)+G2*G7-G2*TP(J-1)*(V(J+1)+G6)-G3*G8
AAY=1./3.*(3.*UU-PHE**2)
RR=-G2*G7*TP(J-1)-G3*Z1(J)/Z(J)*TP(J+1)
BEE=1./27.*(2.*PHE**3-9.*PHE*UU+27.*RR)

C
DIS1=UU**2-4.*PHE*RR
IF (DIS1.LE.0.) GO TO 47
TP(J)=(-UU+SQRT(DIS1))/(2.*PHE)
GO TO 48
47 TP(J)=C.5*(T(J)+TP(J-1))
48 DN 49 LEL=1,10
HOPE=G8*TP(J)**3+PHE*TP(J)**2+UU*TP(J)+RR
HOP=ABS(HOPE)
DHOPDT=3.*G8*TP(J)**2+2.*PHE*TP(J)+UU
AZ9=800.
AZ8=.0001*DHOPDT
IF (AZ8.LT.AZ9) AZ9=AZ8
IF (HOP.LT.AZ9) GO TO 50
TP(J)=TP(J)-HOPE/DHOPDT
XR(1)=TP(J)
49 CONTINUE
WRITE (6,105)
KSTAR=KSTAR+1
IF (KSTAR.GT.25) GO TO 55
50 CONTINUE
TEST(J)=BEE**2/4.+AAY**3/27.
IF (TEST(J).LE.0..AND.TP(J).GT.TPP) GO TO 51
GO TO 54
51 AQ(1)=G8
AQ(2)=PHE+XR(1)*G8
AQ(3)=UU+XR(1)*AQ(2)
XQ1=-AQ(2)/(2.*AQ(1))
DISC=XQ1*XQ1-AQ(3)/AQ(1)
52 IF (DISC.LT.0.) GO TO 54
C
53 XQ2=SQRT(DISC)
TP(J)=XQ1+XQ2
IF (TP(J).GT.TPP) TP(J)=XR(1)
C
C--- FOR SIGNIFICANCE OF TEST(J), SEE COMMENT UNDER STEP 13
54 TWP(J)=(TW(J)+(D2-1.0)*TP(J)+D1)/D2
GO TO 56
55 IF (TIME.GT.PM1) DETY=DETY-0.005
IF (TIME.LE.PM1) DETY=DETY-0.01
DT=DETY
TIME=TIMY+DT
IF (TIME.LE.TIMY) GO TO 1
GO TO 36
C
THE FOLLOWING TWO EQUATIONS ARE SPECIFIC HEAT VS TEMP. FOR AN
C ASSUMED MASSIVE STAINLESS STEEL LID AT THE TOP OF THE TANK
56 IF (SPSS-499.0) 61,57,57
57 IF (TW(1)-75.0) 58,59,59
58 CPW(1)=C.010
GO TO 61
59 IF (TW(1).GT.220.) GO TO 60
CPW(1)=C.000418*TW(1)-C.0203

GO TO 61

```

```

60      W=(TW(1)-220.)/126.67
        CPW(1)=(0.0018*W-0.0127)*W+0.0374)*W+0.071
61      C5(1)=1.0/(TICK(1)*SPWSS)
        C9(1)=XPI*DX*DIA*TICK(1)*SPWSS
C
        D1=C5(1)*DT*QOUT/CPW(1)
        D2=1.0+C5(1)*DT*H(1)/CPW(1)
        KLAMP=KLAMP+1
C
        TWP(1)=(TW(1)+(D2-1.0)*TP(1)+D1)/D2
C
        IF (KLAMP.LT.3) GO TO 62
        IF (ERRP.LT..05) GO TO 62
        IF (ERRP.GT..05.AND.ISTAR.GT.6) GO TO 62
        GO TO 71
C
C
C          STEP-9-
C          FIND HEAT TRANSFER COEFFICIENT AT NEW TIME
C
62      IF (HCONST) 1,63,65
63      DO 64 J=1,N
        XL=ULLAGE+X(J)
64      CALL FCOEFF (TP(J),TWP(J),P,XL,H(J),ZCONST,HMULT,HEXP,XMOLEC)
65      CONTINUE
C
C
C          STEP-10-
C          FIND COMPRESSIBILITY FACTORS AT NEW TIME
C
        DO 66 K=1,N
66      ZAV(K)=Z(K)
        IF (ZCONST) 1,67,69
67      DO 68 J=1,N
68      CALL CCMPRS (TP(J),P,Z(J),Z1(J),Z2(J),XMOLEC)
69      CONTINUE
C
C
C          STEP-11-
C          FIND SPECIFIC HEATS AT NEW TIME
C
        DO 70 J=1,N
70      CALL SPHEAT (TP(J),TWP(J),CP(J),CPW(J),XMOLEC)
C
C
71      CONTINUE
        IF (KLAMP.LT.3) GO TO 46
C
C
C          STEP-12-
C          FIND VELOCITIES AT NEW TIME
C
        CALL INTERP (FLOW,TIME3,MFLOW,TIME,FLOWNP)
        V(N)=FLOWNP/AREA(N)
        IF (LOCM.GE.3) GO TO 89
C

```



```

      DO 72 J=2,N
      K=NP-J
      V(K)=(TP(K)*V(K+1)-(DX/(DT*Z(K)))*(Z1(K)*(TP(K)-T(K))+Z2(K)*TP(K)
1*DPDT*CX/(Z(K)*PP)))/(TP(K)+(Z1(K)/Z(K))*(TP(K+1)-TP(K))-(2.0*DX*TP
2(K)*(DRCX(K+1)+DRDX(K)))/(RAD(K+1)+RAD(K)))
      IF (V(K).LT.0.) GO TO 73
72    CONTINUE
      ERRP=C.
      GO TO 82
73    LCOM=LCOM+1
      WRITE (6,119)
      GO TO 55
74    DO 75 J=1,N
      VP(J)=.5
75    CONTINUE
76    CONTINUE
      DO 78 J=1,N
      VIP=VP(J)
      IF (VIP.EQ.0.) GO TO 78
      ERR=(V(J)-VP(J))/VP(J)
      ERR=ABS(ERR)
      IF (ERR-ERRP) 78,78,77
77    ERRP=ERR
78    CONTINUE
      IF (ERRP-.004) 89,89,79
79    IF (ISTAR.EQ.36) GO TO 87
80    DO 81 J=1,N
      VP(J)=V(J)
81    CONTINUE
      ISTAR=ISTAR+1
      IF (ISTAR.GT.32) GO TO 103
82    IF (ISTAR-40) 46,46,84
83    IF (ISTAR) 74,74,76
84    IF (ERRP-.10) 85,85,86
85    ERROR=ERRP*100.
      GO TO 104
86    WRITE (6,108)
      WRITE (6,114) ERROR
      WRITE (6,115) TIME
      WRITE (6,110)
      WRITE (6,112) (TP(J),J=1,N,10)
      WRITE (6,116)
      WRITE (6,112) (TWP(J),J=1,N,10)
C      AT THIS POINT THE PROGRAM WILL CONTINUE REGARDLESS OF THE ERROR
C      OPTION II IS TO REDUCE THE TIME INCREMENT, PROCEED TO STEP 5
      GO TO 89
87    DO 88 J=1,N
88    V(J)=(V(J)+VP(J))/2.
      GO TO 8C
C
C      STEP-13-
C      FIND GAS FLOW RATE AND TOTAL GAS ADDED UP TO THE NEW TIME
C
89    CONTINUE
      IF (TP(1).GT.TPP) TPP=TP(1)
C      IF TEST(J) IS GREATER THAN 0-ONE REAL AND TWO CONJUGATE

```

```

C      IMAGINARY ROOTS-- IF TEST(J)=0., THERE WILL BE THREE
C      REAL ROOTS -- IF TEST(J) IS LESS THAN 0-THERE WILL BE
C      THREE REAL AND UNEQUAL ROOTS.
      DO 91 J=1,N
      IF (TP(J)-TPP) 91,91,90
90     WRITE (6,109) TP(J),J,TIME,TEST(J)
91     CONTINUE
      GASB=C.5*AREA(1)/TP(1)/Z(1)+0.5*AREA(N)/TP(N)/Z(N)
      DO 92 J=2,NJ
92     GASB=GASB+AREA(J)/TP(J)/Z(J)
      GASB=GASB*C4*P

C      GSRATE=(GASB-GASA)/DT
      GAS=GASB-GSTART
      GASCHK=GASCHK+0.25*(V(2)+VHOLD)/(C8/AREA(2))*DT*(PHCLD/ZHOLD/T(2)+
1P/Z(2)/TP(2))

C
C      STEP-14-
C      FIND HEAT FLOW RATE TO WALL AND TOTAL HEAT ADDED TO WALL
C
      DQ=C9(1)*CPW(1)*(TWP(1)-TW(1))
      DO 93 J=2,N
93     DQ=DQ+RAD(J)*SQRT(1.0+DRDX(J)**2)*CPW(J)*(TWP(J)-TW(J))*C9(J)
      Q=Q+DQ

C
C      WRITE OUT RESULTS
C
      ITER1=ITER1+1
      IF (ITER1-IWRITE) 95,94,94
94     CALL WRITE2
      ITER1=C
95     IF (TIME.GE.ENDRMP) CALL WRITE2
      IF (TIME.GE.ENDRMP) RAMP=1000.

C
C      STEP-15-
C      CHECK TO SEE IF END TIME HAS BEEN REACHED
C
      IF (TIME-ENDTIM) 96,101,101

C
C      END TIME NOT REACHED - PREPARE FOR ANOTHER STEP
C
96     IF (TIME.GT.PM1) DT=0.1
      IF (TIME.GT.PM2) DT=0.2
      IF (TIME.GT.PM3) DT=0.5
      IF (TIME.GT.PM4) DT=1.0
      DETY=DT
      TIMY=TIME
      TYME=TIME+DT
      TEIM=TYME+.1
      IF (TEIM.GT.ENDTIM) TYME=ENDTIM
      CALL INTEP (FLOW,TIME3,MFLOW,TYME,FLOWP)
      CHECK=FLOWP

```

```

VP=FLOWP/AREA(N)
IF (TIME.EQ.ENDTIM) DT=ENDTIM-TIME
IF (CHECK.EQ.0.) GO TO 97
DT=DX/(V(N)+VP)*2.
97  TIME=TIME+DT
C
DO 98 J=1,N
T(J)=TP(J)
98  TW(J)=TWP(J)
GASA=GASB
LDDM=C
C
IF (CHECK-0.) 99,99,100
99  NJ=N-1
GO TO 40
100 NJ=N
N=N+1
NP=N+1
DRDX(N)=(RAD(NP)-RAD(N))/(X(NP)-X(N))
DRDX(NP)=CRDX(N)
GO TO 40
C
C
C          STEP-16-
C          END TIME EXCEEDED - INTERPOLATE CONDITIONS AT END TIME
C
101  RATIO=(ENDTIM-TIME+DT)/DT
TIME=ENDTIM
C
DO 102 J=1,N
TP(J)=T(J)+RATIO*(TP(J)-T(J))
102  TWP(J)=TW(J)+RATIO*(TWP(J)-Tw(J))
C
Q=Q-DQ+RATIO*DQ
GAS=GAS-GASB+GASA+RATIO*(GASB-GASA)
GASCHK=GASCHK-GASB+GASA+RATIO*(GASB-GASA)
C
C          STEP-17-
C
CALL WRITE2
GO TO 1
C
103  WRITE (6,111)
WRITE (6,112) (V(J),J=1,N,10)
WRITE (6,113) ISTAR
GO TO 82
104  WRITE (6,114) ERROR
WRITE (6,110)
WRITE (6,112) (TP(J),J=1,N,10)
WRITE (6,115) TIME
WRITE (6,111)
WRITE (6,112) (V(J),J=1,N,10)
GO TO 89
C
C          *****
C

```

# FORMAT STATEMENTS

```

C
C
C
C
105  FORMAT (1HK,71H  SOLUTION TO CUBIC BY NEWTON-RHAPSON REQUIRES MORE
      1  THAN 10 ITERATIONS )
106  FORMAT (1HL,3CX,29H  TANK PRESSURIZATION PROGRAM/1HJ)
107  FORMAT (80H
      1
      )
108  FORMAT (1HK,32H ERROR GREATER THAN ACCEPTABLE )
109  FORMAT (1HL,5X,13H  GAS T(R) = F6.1,5H  J= I3,9H  TIME = F5.1,9H
      1SECONDS,9H  TEST = E13.5,2X,40H  COMPUTED TEMP. GREATER THAN BOUND
      2APY )
110  FORMAT (1HL,10X,43H  ULLAGE GAS TEMP PROFILE IN PROGRAM UNITS /1X)
111  FORMAT (1HL,10X,108H INSTANTANEOUS ULLAGE GAS FLORATES FROM TOP TO
      1 INTERFACE-NEGATIVE VALUES ARE UNSTABLE-RATES IN PROGRAM UNTS /1X)
112  FORMAT (1P8G15.7)
113  FORMAT (1HL,10X,15H  ITERATIONS = I3)
114  FORMAT (1HL,10X,18H  PERCENT ERROR = F5.1,10H  PERCENT /1X)
115  FORMAT (1HL,10X,17H  TIME IN RAMP = F5.1,10H  SECONDS /1X)
116  FORMAT (1HL,10X,43H  ULLAGE WALL TEMP PROFILE - PROGRAM UNITS /1X)
117  FORMAT (1HL,2X,17H  GAS SUPPLIED = F7.3,5H  LBS,2X,14H  GAS CHECK
      1= F7.3,5H LBS,2X,14H  RAMP TIME = F7.2,9H  SECONDS)
118  FORMAT (1HK,2X,13H  GAS FLOW = E13.5,9H  LBS/SEC,2X,15H  ITERATION
      1S = I3,2X,17H  HEAT TO WALL = E13.5,5H  BTU)
119  FORMAT (1HK,50H ONE OR MORE NEGATIVE GAS VELOCITIES ARE COMPUTED )
1015 FORMAT (1HK,23H  INITIAL ULLAGE GAS = F6.3,5H  LBS)
1050 FORMAT (1HK, 25H  INITIAL HEAT TO WALL = F7.1, 5H  BTU)
2015 FORMAT (1HK,23H  INITIAL ULLAGE GAS = F6.3,10H  KILCGRAM)
2050 FORMAT (1HK, 25H  INITIAL HEAT TO WALL = E11.4, 7H  JOULE)
      END

```

# TANK PRESSURIZATION PROGRAM

PRESSURIZATION OF 13 FT. ALUMINUM TANK  
FIVE PERCENT ULLAGE HYDROGEN PRESSURANT  
END OF RAMP 19.6 SECONDS

\$OTPTS

MTGAS = 8, MDATA= 14, MFLOW = 1, MTSAT = 8, MTRULK= 1,  
MQOUT = 1, MQIN = 1, MTWIN = 8, MTGIN = 10, MRAD = 0,  
MTICK = 20,  
\$ ENC

## INPUT DATA

INITIAL NUMBER OF NETPOINTS = 40.  
INITIAL ULLAGE = 1.681 FEET  
TANK RADIUS = -1.000 FEET

TANK WALL SPECIFIC WEIGHT = 169.3 LBS/CUBIC FOOT  
MOLECULAR WEIGHT = 2.0

GAS TEMP, DEG R VS TIME, SECONDS

307.9	C.
309.8	6.3
309.5	12.7
308.2	19.6
309.5	25.9
309.5	45.1
308.8	51.5
310.3	52.9

PRESSURE, LBS/SQ FT VS TIME, SECONDS

2556.2	C.
2707.2	3.5
2900.3	6.3
3162.0	9.8
3456.0	11.0
3956.0	12.7
4608.0	15.5
5472.0	17.5
6264.7	19.1
6710.2	19.6
6910.0	21.5
7050.0	23.5
7182.0	32.3
7193.0	52.9

FLOW RATE, CU FT/SEC VS TIME, SECONDS

C.

0.

SATURATION TEMP, DEG P VS TIME, SECONDS

37.7 0.  
 38.5 6.3  
 40.7 12.7  
 44.8 19.6  
 46.5 25.9  
 46.4 45.1  
 46.4 51.5  
 45.4 52.9

BLK TEMP, DEG P VS TIME, SECONDS

36.7 C.

OUTSIDE HEATING RATE, BTU/SQ FT-SEC VS TIME, SECONDS

C.0100 0.

INSIDE HEATING RATE, BTU/LINEAR FT-SEC VS TIME, SECONDS (Note Q IND = (-Q IN) by the program)

C.2500 0.

INITIAL TEMPERATURE-DEG. RANKINE

X COORDINATE WALL TEMPERATURE GAS TEMPERATURE

C. 215.0 206.0  
 C.04 214.9 202.3  
 C.09 210.8 198.5  
 C.13 206.7 194.8  
 C.17 202.6 191.1  
 C.22 198.5 187.3  
 C.26 194.4 183.6  
 C.30 190.3 179.9  
 C.34 186.2 176.1  
 C.39 182.2 172.4  
 C.43 178.1 168.7  
 C.47 174.0 164.9  
 C.52 169.9 161.2  
 C.56 165.8 157.4  
 C.60 161.7 153.7  
 C.65 157.8 149.4  
 C.69 153.5 145.1  
 C.73 150.1 140.7  
 C.78 146.2 136.4  
 C.82 142.0 131.4  
 C.86 137.5 125.3  
 C.90 133.0 119.3  
 C.95 128.5 113.3  
 C.99 123.5 107.2  
 1.03 119.1 101.4  
 1.08 114.1 95.6

1.12	109.2	89.7
1.16	104.2	83.9
1.21	99.3	78.1
1.25	94.8	72.5
1.29	90.2	66.9
1.34	85.7	61.7
1.38	81.2	56.5
1.42	78.0	52.0
1.47	75.2	48.1
1.51	72.5	44.5
1.55	70.1	41.9
1.59	67.8	39.3
1.64	65.4	38.1
1.68	63.0	37.0

TANK RADIUS (FEET) VS AXIAL DISTANCE (FEET)  
-0.000 -0.00

HEAT TRANSFER COEFFICIENT WILL BE COMPUTED  
FMULT = 0. HEXP = 0.

A PEAL GAS IS ASSUMED

THE PRESSURANT IS HYDROGEN

# RESULTS

INSTANTANEOUS ULLAGE GAS FLICRATES FROM TOP TO INTERFACE-NEGATIVE VALUES ARE UNSTABLE-RATES IN PROGRAM UNITS

0.3354064 2.3888280E-02 5.0440085E-03 3.0610921E-03

INITIAL ULLAGE GAS = 2.570 LBS

INITIAL HEAT TO WALL = 0. HTU

TIME = 6.70 SECONDS		GAS SUPPLIED = 0.078 LBS		GAS FLOW = 0.0174 LBS/SEC		HEAT TO WALL =		5.6 BTU		INLET VEL = 1.8756 FEET/SEC	
CHECK (IN GAS =		0.078 LBS		GAS FLOW = 0.0174 LBS/SEC		HEAT TO WALL =		5.6 BTU		INLET VEL = 1.8756 FEET/SEC	
X, FEET	WALL T (P)	GAS T (R)	X, FEET	WALL T (R)	GAS T (R)	HEAT TO WALL =	5.6 BTU	OUTLET VEL = 0.0000 FEET/SEC	WALL T (R)	GAS T (R)	FEET/SEC
0.	219.0	205.8	0.04	215.0	309.1				0.05	210.9	306.9
0.13	207.1	303.9	0.17	202.9	300.1				0.22	198.8	295.8
0.26	194.7	290.6	0.30	190.5	283.5				0.34	186.4	272.1
0.39	182.3	255.5	0.43	178.1	235.6				0.47	174.1	216.3
0.52	170.0	200.4	0.56	165.5	188.2				0.60	161.8	179.3
0.65	157.6	172.2	0.69	154.0	166.1				0.73	150.2	160.5
0.78	146.2	155.0	0.82	142.1	149.4				0.86	137.6	143.5
0.90	133.1	137.0	0.95	128.5	130.2				0.99	124.0	123.1
1.03	119.1	114.0	1.03	114.1	109.1				1.12	105.1	102.2

1.16	104.1	95.3	1.21	99.2	88.6	1.25	54.5	82.0
1.29	80.9	75.5	1.34	85.2	69.3	1.38	60.5	63.2
1.42	77.0	57.8	1.47	74.0	53.1	1.51	70.9	48.9
1.55	68.2	45.7	1.59	65.3	42.7	1.64	62.8	41.0
1.68	36.7	39.6						

GAS TEMP = 310.0 J= 14 TIME = 19.6 SECONDS TEST = -0.17600E+21 COMPUTED TEMP. GREATER THAN BOUNDARY

GAS TEMP = 310.4 J= 15 TIME = 19.6 SECONDS TEST = -0.11034E+21 COMPUTED TEMP. GREATER THAN BOUNDARY

GAS TEMP = 310.9 J= 16 TIME = 19.6 SECONDS TEST = -0.54588E+20 COMPUTED TEMP. GREATER THAN BOUNDARY

GAS TEMP = 311.2 J= 17 TIME = 19.6 SECONDS TEST = -0.91494E+19 COMPUTED TEMP. GREATER THAN BOUNDARY

GAS TEMP = 311.3 J= 18 TIME = 19.6 SECONDS TEST = 0.26148E+20 COMPUTED TEMP. GREATER THAN BOUNDARY

GAS TEMP = 311.0 J= 19 TIME = 19.6 SECONDS TEST = 0.50505E+20 COMPUTED TEMP. GREATER THAN BOUNDARY

GAS TEMP = 310.0 J= 20 TIME = 19.6 SECONDS TEST = 0.63250E+20 COMPUTED TEMP. GREATER THAN BOUNDARY

TIME = 19.60 SECONDS GAS SUPPLIED = 0.513 LBS HEAT TO WALL = 0.1443 LBS/SEC INLET VEL = 6.1440 FEET/SEC

CHECK ON GAS		GAS FLOW		OUTLET VEL = 0.0000 FEET/SEC		INLET VEL = 6.1440 FEET/SEC		
X, FEET	WALL T(F)	GAS T(R)	X, FEET	WALL T(R)	GAS T(R)	X, FEET	WALL T(R)	GAS T(R)
0.	219.1	309.2	0.04	215.1	308.1	0.09	211.0	307.8
0.13	208.1	307.7	0.17	204.0	307.5	0.22	199.9	307.5
0.26	195.8	307.6	0.30	191.8	307.7	0.34	187.7	307.9
0.39	183.6	308.2	0.43	179.5	308.5	0.47	175.8	309.0
0.52	171.5	305.5	0.56	168.0	310.0	0.60	164.2	310.4
0.65	160.4	310.5	0.69	157.1	311.2	0.73	153.2	311.3
0.78	149.4	311.0	0.82	145.2	310.0	0.86	140.7	307.6
0.91	135.1	303.1	0.95	131.4	295.5	0.99	126.8	284.2
1.03	121.8	269.3	1.08	116.8	251.5	1.12	111.7	232.2
1.16	106.7	212.7	1.21	101.6	193.7	1.25	96.5	175.6
1.29	92.1	158.4	1.34	87.2	141.9	1.38	82.2	126.1
1.42	78.2	111.0	1.47	74.5	97.2	1.51	70.8	85.0
1.55	67.4	74.8	1.59	63.8	66.7	1.64	60.8	61.1
1.68	36.7	44.8						



TIME = 20.10 SECONDS GAS SUPPLIED = 0.9140 LBS HEAT TO WALL = 0.0328 LBS/SEC INLET VEL = 1.6010 FEET/SEC

CHECK ON GAS = 0.969 LBS GAS FLOW = 0.0328 LBS/SEC OUTLET VEL = 0.0000 FEET/SEC

X, FEET	WALL T(R)	GAS T(R)	X, FEET	WALL T(R)	GAS T(R)	X, FEET	WALL T(R)	GAS T(R)
0.	219.1	308.3	0.04	215.1	307.7	0.09	211.0	306.2
0.13	208.2	305.0	0.17	204.1	304.3	0.22	200.0	304.0
0.26	195.5	304.0	0.30	191.8	304.2	0.34	187.7	304.6
0.39	183.6	305.1	0.43	179.6	305.6	0.47	175.9	306.2
0.52	172.0	306.8	0.56	168.2	307.4	0.60	164.4	308.0
0.65	160.6	308.5	0.69	157.3	309.0	0.73	153.5	309.2
0.78	149.6	309.1	0.82	145.5	308.2	0.86	141.0	306.3
0.90	136.4	302.2	0.95	131.8	295.2	0.99	127.1	284.5
1.03	122.2	270.1	1.08	117.1	252.6	1.12	112.1	233.5
1.16	107.0	213.5	1.21	102.0	194.5	1.25	97.2	176.7
1.29	92.4	159.4	1.34	87.5	142.7	1.38	82.5	126.8
1.42	78.4	111.7	1.47	74.7	97.8	1.51	70.9	85.5
1.55	67.5	75.2	1.59	63.9	67.0	1.64	60.9	61.4
1.68	36.7	44.5						

• • •

TIME = 50.10 SECONDS GAS SUPPLIED = 1.632 LBS HEAT TO WALL = 0.0080 LBS/SEC INLET VEL = 0.4490 FEET/SEC

CHECK ON GAS = 1.632 LBS GAS FLOW = 0.0080 LBS/SEC OUTLET VEL = 0.0000 FEET/SEC

X, FEET	WALL T(R)	GAS T(R)	X, FEET	WALL T(R)	GAS T(R)	X, FEET	WALL T(R)	GAS T(R)
0.	219.2	305.0	0.04	215.5	306.8	0.09	211.4	300.5
0.13	211.1	293.4	0.17	207.0	286.1	0.22	202.9	278.9
0.26	198.8	271.5	0.30	194.7	265.1	0.34	190.6	258.7
0.39	186.5	252.6	0.43	182.5	247.0	0.47	179.5	242.0
0.52	176.0	237.5	0.56	172.7	233.5	0.60	169.6	230.2
0.65	166.6	227.6	0.69	165.2	226.0	0.73	162.2	225.1
0.78	155.1	224.8	0.82	155.8	224.5	0.86	152.3	225.1
0.90	143.3	225.3	0.95	155.2	225.1	0.99	141.4	224.0
1.03	137.2	221.5	1.08	152.3	216.6	1.12	128.0	208.6
1.16	122.8	197.6	1.21	117.5	194.2	1.25	112.1	169.7
1.29	106.7	155.0	1.34	101.1	140.6	1.38	95.3	126.4
1.42	90.7	112.7	1.47	84.0	99.7	1.51	78.4	87.8
1.55	73.5	77.4	1.59	68.3	69.0	1.64	64.6	63.0
1.68	36.7	45.4						

# APPENDIX D

## SUBROUTINES - COMMON TO BOTH PROGRAMS

### SUBROUTINE SINTS

#### DIMENSION

```

1      TGAS(30),TIME1(30),PCDATA(30),TIME2(30),
2      FLOW(30),TIME3(30),TSAT(30),TIME4(30),
3      TBULK(30),TIME5(30),QCUTD(30),TIME6(30),
4      CIND(30),TIME7(30),ZAV(150),
5      TWIND(30),DIST1(30),TGIND(30),DIST2(30),
6      X(150),T(150),TP(150),TW(150),TWP(150),V(150),
7      CP(150),CPW(150),H(150),Z(150),Z1(150),Z2(150),
8      RAD(150),AREA(150),YRAD(150),XRAD(150),ORDX(150)

```

#### DIMENSION

```

1      C5(150),C9(150),YTICK(50),XXT(50),TICK(150)
2      ,TWBK(30),DIST7(30),TWCU(30),DIST8(30),TSTN(30),DIST9(30),
3      TWAL(30),DIS11(30),CPBK(150),TWB(150),TB(150),CPCU(150),
4      TWC(150),TC(150),CPST(150),TST(150),TZ(150),CPAL(150),
5      TALS(150),TRC(150),TTT(150),PRAM(150)

```

#### COMMON

```

1      X,T,TP,TW,TWP,V,CP,CPW,TGAS,TIME1,MTGAS,PCDATA,TIME2,MPDATA,
2      FLOW,TIME3,MFLOW,TSAT,TIME4,MTSAT,TBULK,TIME5,MTBULK,QCUTD,
3      TIME6,MQCUTD,QIND,TIME7,MQIN,N,NP,XN,ULLAGE,RADIUS,DQ,
4      SPWGT,XMOLEC,GSTART,HCONST,TIME,GAS,Q,GASCHK,GSRATE,DT,
5      ZCCNST,H,HMULT,HEXP,YRAD,XRAD,MRAD,TNKWT,CQTR,QIN,UNUMS,
6      MTWIN,MTGIN,MTICK,MTBAK,MTCU,MTSS,MTAL,
7      TWIND,DIST1,TGIND,DIST2,YTICK,XXT,TWBK,DIST7,
8      TWAL,DIS11,TWCU,DIST8,TSTN,DIST9

```

#### COMMON

```

1      CARAD,ADIFU,SPWSS,DIA,RCONST,TADD,AB,AIC,A3S,A5B,WTB,WTIC,
2      WTS,WTSB

```

\*\*\*\*\*

WHEN USING THIS SUBROUTINE FOR THE PRESSURIZATION PROGRAM - USE  
THE SAME DIMENSION AND COMMON APPEARING IN THE MAIN PROGRAM .

\*\*\*\*\*

IF(RADIUS .LE. 0.0) GO TO 10

RADIUS = RADIUS/0.3048

10 ULLAGE = ULLAGE/0.3048

CARAD = CARAD/0.3048

HCCNST = HCCNST/3.1524808/1.8

ADIFU = ADIFU/.09290304

SPWGT = SPWGT/16.018463

SPWSS = SPWSS/16.018463

DIA = DIA/0.3048

RCCNST = RCCNST/0.3048

TACC = TACC \* 1.8

AB = AB/.09290304

AIC = AIC/.09290304

A3S = A3S/.09290304

A5B = A5B/.09290304

```

      WTE = WTB/.45359237
      WTIC = WTIC/.45359237
      WT3S = WT3S/.45359237
      WT5B = WT5B/.45359237
      IF(MTGAS .LT. 1)GO TO 102
      DO 101 J=1,MTGAS
101  TGAS(J) = TGAS(J) * 1.8
102  IF(MPCDATA .LT. 1)GO TO 106
      DO 104 J=1,MPDATA
104  PCATA(J) = PDATA(J)/47.880258 * 0.1000000E+07
106  IF(MFLOW .LT. 1)GO TO 109
      DO 108 J=1,MFLOW
108  FLOW(J) = FLOW(J)/.3048**3
109  IF(MTSAT .LT. 1) GO TO 112
      DO 110 J=1,MTSAT
110  TSAT(J) = TSAT(J) * 1.8
112  IF(MTBULK .LT. 1)GO TO 116
      DO 114 J=1,MTBULK
114  TBULK(J) = TBULK(J) * 1.8
116  IF(MQOUT .LT. 1)GO TO 120
      DO 117 J=1,MQOUT
117  QOUTD(J) = QOUTD(J)/11348.931
120  IF(MQIN .LT. 1)GO TO 130
      DO 121 J=1,MQIN
121  QIND(J) = QIND(J)/1054.3503 * .3048
130  IF(MTWIN .LT. 1)GO TO 134
      DO 131 J=1,MTWIN
      TWIND(J)= TWIND(J)*1.8
131  DIST1(J)= DIST1(J)/0.3048
134  IF(MTGIN .LT. 1)GO TO 138
      DO 135 J= 1,MTGIN
      TGIND(J)= TGIND(J)*1.8
135  DIST2(J)= DIST2(J)/0.3048
138  IF(MRAD .LT. 1)GO TO 141
      DO 139 J=1,MRAD
      YRAD(J)= YRAD(J)/0.3048
139  XRAD(J)= XRAD(J)/0.3048
141  IF(MTICK .LT. 1)GO TO 144
      DO 142 J=1,MTICK
      YTICK(J)= YTICK(J)/0.3048
142  XXT(J)= XXT(J)/0.3048
144  IF(MTBAK .LT. 1)GO TO 147
      DO 145 J=1,MTBAK
      TWBK(J)= TWBK(J)*1.8
145  DIST7(J)= DIST7(J)/0.3048
147  IF(MTCU .LT. 1)GO TO 150
      DO 148 J=1,MTCU
      TWCU(J)= TWCU(J)*1.8
148  DIST8(J)= DIST8(J)/0.3048
150  IF(MTSS .LT. 1)GO TO 153
      DO 151 J=1,MTSS
      TSTN(J)= TSTN(J)*1.8
151  DIST9(J)=DIST9(J)/0.3048
153  IF(MTAL .LT. 1)GO TO 156
      DO 154 J=1,MTAL
      TWAL(J)= TWAL(J)*1.8
154  DIS11(J)=DIS11(J)/0.3048
156  CONTINUE

```

C

RETURN

C

```

C   FOR THE PRESSURIZATION PROGRAM - REMOVE ALL STATEMENTS FROM 144
C   THROUGH 154 - CHANGE STATEMENT NUMBER 156 TO 144 .
C
C   END

```

```

C   SUBROUTINE SPHEAT(T,TW,CP,CPW,XMOLEC)
C
C   DIMENSION CPTEMP(15),CPWALL(15),CTEMP(15),CGAS(15)
C
C   DATA FOR SP HT OF ALUM ALLOY 2219-T852
C   (THERMOPHYSICAL PROPERTIES RESEARCH CENTER-PURDUE UNIV.)
C   DATA (CPTEMP(J),CPWALL(J),J=1,15)/36...0020,45...0042,54...0074,72
1...0181,90...0330,108...0513,126...0692,144...0837,162...0994,180.
2...1620,270...1600,315...1720,360...1830,432...2029,540...2080/
C
C   DATA FOR SPECIFIC HEAT OF HYDROGEN AT 50 PSIA (NBS)
C   DATA (CTEMP(J),CGAS(J),J=1,15)/45.5,3.65,48.8,3.40,50.0,3.30,55.0
1,3.05,58.0,2.92,60.0,2.85,65.0,2.76,70.0,2.65,80.0,2.52,100.0,
22.60,200.0,2.72,250.0,2.88,300.0,3.08,350.0,3.28,450.0,3.42/
C
C   IF (TW-CPTEMP(1)) 1,1,3
1   CPW = CPWALL(1)
   GO TO 9
3   DO 7 I=2,15
   IF (TW-CPTEMP(I)) 5,5,7
5   CPW = CPWALL(I-1) + (TW - CPTEMP(I-1))/(CPTEMP(I)-CPTEMP(I-1))
1   *(CPWALL(I)-CPWALL(I-1))
   GO TO 9
C
7   CONTINUE
   CPW = CPWALL(15)
C
9   IF (XMOLEC-3.0) 13,13,11
11  CP = 1.24
   RETURN
C
13  IF (T-CTEMP(1)) 15,15,17
15  CP = CGAS(1)
   RETURN
C
17  DO 21 J=2,15
   IF (T-CTEMP(J)) 19,19,21
19  CP = CGAS(J-1)+(T-CTEMP(J-1))/(CTEMP(J)-CTEMP(J-1))*
1   (CGAS(J)-CGAS(J-1))
   RETURN
C
21  CONTINUE
C
   CP = CGAS(15)
   RETURN
C
C
C   END

```

# SUBROUTINE WRITE 1

```

C
C
      DIMENSION
1      TGAS(30),TIME1(30),PCDATA(30),TIME2(30),
2      FLOW(30),TIME3(30),TSAT(30),TIME4(30),
3      TBULK(30),TIME5(30),QOUTD(30),TIME6(30),
4      CIND(30),TIME7(30),ZAV(150),
5      TWIND(30),DIST1(30),TGIND(30),DIST2(30),
6      X(150),T(150),TP(150),TW(150),TWP(150),V(150),
7      CP(150),CPW(150),H(150),Z(150),Z1(150),Z2(150),
8      RAD(150),AREA(150),YRAD(150),XRAD(150),DRDX(150)
      DIMENSION
1      C5(150),C9(150),YTICK(50),XXT(50),TICK(150)
2      ,TWBK(30),DIST7(30),TWCU(30),DIST8(30),TSTN(30),DIST9(30),
3      TWAL(30),DIS11(30),CPBK(150),TWB(150),TB(150),CPCU(150),
4      TWC(150),TC(150),CPST(150),TST(150),TZ(150),CPAL(150),
5      TALS(150),TBC(150),TTT(150),PRAM(150)
C
      COMMON
1      X,T,TP,TW,TWP,V,CP,CPW,TGAS,TIME1,MTGAS,PCDATA,TIME2,MPDATA,
2      FLOW,TIME3,MFLOW,TSAT,TIME4,MTSAT,TBULK,TIME5,MTBULK,QOUTD,
3      TIME6,MQOUT,QIND,TIME7,MQIN,N,NP,XN,ULLAGE,RADIUS,DQ,
4      SPWGT,XMOLEC,GSTART,HCONST,TIME,GAS,Q,GASCHK,GSRATE,DT,
5      ZCONST,H,HMULT,HEXP,YRAD,XRAD,MRAD,TNKWT,CQTR,QIN,UNUMS,
6      MTWIN,MTGIN,MTICK,MTBK,MTCU,MTSS,MTAL,
7      TWIND,DIST1,TGIND,DIST2,YTICK,XXT,TWBK,DIST7,
8      TWAL,DIS11,TWCU,DIST8,TSTN,DIST9
C
      COMMON
1      CARAD,ADIFU,SPWSS,DIA,RCONST,TADD,AB,A1C,A3S,A5B,WTB,WTIC,
2      WT3S,WT5B
C
      WHEN USING THIS SUBROUTINE FOR THE PRESSURIZATION PROGRAM - USE
      THE SAME DIMENSION AND COMMON APPEARING IN THE MAIN PROGRAM .
C
      WRITE (6,1007)
C
1007  FORMAT (1HL, 12H INPUT DATA)
C
      N = XN
      DX = ULLAGE/(XN-1.0)
      DO 30 J=2,N
      XJTICK = J-1
30    X(J) = DX * XJTICK
      X(1) = 0.
      DO 31 J=1,N
      CALL INTERP (TWIND,DIST1,MTWIN,X(J),TW(J))
31    CALL INTERP (TGIND,DIST2,MTGIN,X(J),T(J))

```

```

      IF (UNUMS) 100, 101, 100
101  WRITE (6, 1010)                XN, ULLAGE, RADIUS, SPWGT, XMOLEC
C
1010  FORMAT (1HL, 9X, 32H  INITIAL NUMBER OF NETPOINTS = F3.0/
1     10X, 19H  INITIAL ULLAGE = F6.3, 6H  FEET/
2     10X, 16H  TANK RADIUS = F6.3, 6H  FEET/
3     10X, 30H  TANK WALL SPECIFIC WEIGHT = F6.1, 16H  LBS/CUBIC FOOT/
4     10X, 21H  MOLECULAR WEIGHT = F3.1)
      WRITE (6, 1008)
C
1008  FORMAT (1HL, 9X, 4CH  GAS TEMP, DEG R      VS      TIME, SECONDS/1X)
C
      WRITE (6, 1009)                (TGAS(J), TIME1(J), J = 1, MTGAS)
C
1009  FORMAT (F20.1, F25.1)
C
      WRITE (6, 1030)
C
1030  FORMAT (1HL, 9X, 47H  PRESSURE, LBS/SQ FT      VS      TIME, SECONDS
1     /1X)
C
      WRITE (6, 1009)                (PDATA(J), TIME2(J), J = 1, MPDATA)
C
      WRITE (6, 1031)
C
1031  FORMAT (1HL, 9X, 44H  FLOW RATE, CU FT/SEC VS      TIME, SECONDS      /
1     /1X)
C
      WRITE (6, 1032)                (FLOW(J), TIME3(J), J = 1, MFLOW)
C
1032  FORMAT (F20.4, F25.1)
C
      WRITE (6, 1033)
1033  FORMAT (1HL, 9X, 49H  SATURATION TEMP, DEG R      VS      TIME, SECONDS
1     /1X)
C
      WRITE (6, 1009)                (TSAT(J), TIME4(J), J = 1, MTSAT)
C
      WRITE (6, 1034)
C
1034  FORMAT (1HL, 9X, 44H  BULK TEMP, DEG R      VS      TIME, SECONDS      /1
1     /1X)
C
      WRITE (6, 1009)                (TBULK(J), TIME5(J), J = 1, MTBULK)
C
      WRITE (6, 1035)
C
1035  FORMAT (1HL, 9X, 63H  OUTSIDE HEATING RATE, BTU/SQ FT-SEC      VS
1     TIME, SECONDS      /1X)
C
      WRITE (6, 1032)                (QOUTD(J), TIME6(J), J = 1, MCOUT)
C
      WRITE (6, 1036)
C
1036  FORMAT (1HL, 9X, 62H  INSIDE HEATING RATE, BTU/LINEAR FT-SEC VS
1     TIME, SECONDS      /1X)

```

```

C      WRITE (6,1032) (CIND(J),TIME7(J),J=1,MWIN)
C
C      WRITE (6,1013)
C
1013 FORMAT (1HL,9X,35H  INITIAL TEMPERATURE-DEG. RANKINE /1HK,
1 9X,14H  X COORDINATE,5X,18H  WALL TEMPERATURE,5X,
2 17H  GAS TEMPERATURE/1X)
C
C      WRITE (6,1014) (X(J),TW(J),T(J), J=1,N)
C
1014 FORMAT (F19.2, F22.1, F23.1)
C
C      WRITE (6,2050)
2050 FORMAT(1HL,9X,48H  TANK RADIUS (FEET)  VS AXIAL DISTANCE (FEET)  )
C      WRITE (6,2051) (YRAD(J),XRAD(J), J=1,MRAD)
2051 FORMAT (F20.3,F25.2)
C
C      IF (HCCNST) 5,5,7
C
C      5  WRITE (6,1039)
C
1039 FORMAT (1HK, 46H  HEAT TRANSFER COEFFICIENT WILL BE COMPUTED  )
C      WRITE (6,1051) HMULT, HEXP
1051 FORMAT (1HJ,10H  HMULT = F6.4,5H  HEXP = F6.4)
C      GO TO 9
C
C      7  HCCNST = 3600.*HCCNST
C      WRITE (6,1040) HCCNST
C
1040 FORMAT (1HK, 33H  CONSTANT HEAT TRANSFER COEFF = F6.2,23H  BTU/SQ
1FT-HOUR-DEG R  )
C
C      HCCNST = HCCNST/3600.
C      GO TO 9
100  WRITE (6,4010) XN,ULLAGE,RADIUS,SPWGT,XMOLEC
C
4010 FORMAT (1HL,9X,32H  INITIAL NUMBER OF NETPOINTS = F3.0/
1 10X,19H  INITIAL ULLAGE = F7.3,7H  METER/
2 10X,16H  TANK RADIUS = F6.3,7H  METER/
3 10X,30H  TANK WALL SPECIFIC WEIGHT = F6.1,16H  KG/CUBIC METER/
4 10X,21H  MOLECULAR WEIGHT = F3.1)
C      WRITE (6,4008)
C
4008 FORMAT (1HL,9X,40H  GAS TEMP,DEG K  VS  TIME,SECONDS/1X)
C      WRITE (6,4009) (TGAS(J), TIME1(J), J = 1,MTGAS)
4009 FORMAT (F20.1, F25.1)
C
C      WRITE (6,4030)
4030 FORMAT (1HL,9X,44H  PRESSURE,M-NEWTON/SQ M  VS  TIME,SECONDS/1X)
C      WRITE (6,4009) (PDATA(J),TIME2(J),J=1,MPDATA)
C      WRITE (6,4031)
4031 FORMAT(1HL,9X,44H  FLOW RATE, CU M/SEC  VS  TIME,SECONDS  /
11X)
C      WRITE (6,4032) (FLOW(J),TIME3(J),J=1,MFLOW)
4032 FORMAT (F20.4,F25.1)
C
C      WRITE (6,4033)

```

```

4033 FORMAT (1HL,9X,49H SATURATION TEMP,DEG K      VS      TIME,SECONDS
1      /1X)
WRITE (6,4009) (TSAT(J),TIME4(J),J=1,MTSAT)
WRITE (6,4034)
4034 FORMAT (1HL,9X,44H BULK TEMP,DEG K      VS      TIME,SECONDS      /1
1X)
WRITE (6,4009) (TBULK(J),TIME5(J),J=1,MTBULK)
WRITE (6,4035)
4035 FORMAT (1HL,9X,63H OUTSIDE HEATING RATE,JOULE/SQ M-SEC      VS
1TIME,SECONDS      /1X)
WRITE (6,4032) (QOUTD(J),TIME6(J),J=1,MQOUT)
WRITE (6,4036)
4036 FORMAT (1HL,9X,62H INSIDE HEATING RATE, JOULE/METER-SEC      VS
1TIME,SECONDS      /1X)
WRITE (6,4032) (QIND(J),TIME7(J),J=1,MQIN)
WRITE (6,4013)
4013 FORMAT (1HL,9X,34H INITIAL TEMPERATURE-DEG. KELVIN /1HK,
1 9X,14H X COORDINATE,5X,18H WALL TEMPERATURE,5X,
2 17H GAS TEMPERATURE/1X)
C
WRITE (6,4014) (X(J),TW(J),T(J), J=1,N)
4014 FORMAT (F19.2, F22.1, F23.1)
IF (HCCNST) 50,50,70
50 WRITE (6,4039)
4039 FORMAT (1HK, 46H HEAT TRANSFER COEFFICIENT WILL BE COMPUTED      )
WRITE (6,4051) FMULT, HEXP
C
4051 FORMAT (1HJ,10H HMULT = F6.4,9H HEXP = F6.4)
GO TO 90
70 WRITE (6,4040)
4040 FORMAT (1HK, 33H CONSTANT HEAT TRANSFER COEFF = F6.2,24H WATTS/S
1Q-METER-DEG K      )
50 CONTINUE
WRITE (6,4050)
4050 FORMAT (1HL,9X,48H TANK RADIUS (METER) VS AXIAL DISTANCE (METER)
1)
WRITE (6,2051) (YRAD(J),XRAD(J), J=1,MRAD)
C
9 CONTINUE
C
IF (7CCNST) 13,13,15
13 WRITE (6,1042)
C
1042 FORMAT (1HK, 25H A REAL GAS IS ASSUMED      )
GO TO 17
C
15 WRITE (6,1041)
C
1041 FORMAT (1HK, 27H AN IDEAL GAS IS ASSUMED      )
C
17 CONTINUE
C
IF (XPMOLEC - 3.0) 22,22,23
22 WRITE (6,1011)
C

```



```
1011 FORMAT (1HK, 28H THE PRESSURANT IS HYDROGEN/1H1.9X,9H RESULTS)
C
      GO TO 25
C
      23 WRITE (6,1012)
C
1012 FORMAT (1HK, 26H THE PRESSURANT IS HELIUM/1H1.9X,9H RESULTS)
C
      25 CONTINUE
      RETURN
C
      END
```

SUBROUTINE COMPRS (T,P,Z,Z1,Z2,XMCLEC)

DIMENSION PX(17),TX(20),Z(20,17)

1 IF (3.0-XMCLEC) 3,5,5  
3 Z7 = 1.0  
Z1 = 1.0  
Z2 = 1.0

RETURN

5 CONTINUE

COMPRESSIBILITY DATA (Z(T,P) VALUES COMPUTED FROM DATA OF  
NBS TN 120A)

DATA(PX(J),J=1,17)/ 1440., 2117., 2880., 4320., 5760., 7200.,  
1 8640., 10080., 11520., 12960., 14400., 17280.,  
2 20160., 23040., 25920., 28800., 36000./  
DATA(TX(J),J=1,20)/ 34., 38., 42., 46., 50., 54., 58., 62.,  
1 66., 70., 74., 78., 82., 86., 90., 100.,  
2 120., 140., 160., 200./  
DATA((Z(J,K),J=1,20),K=1,9)/  
1 .9153,.9345,.9482,.9577,.9644,.9695,.9734,.9764,.9789,.9809,  
2 .9825,.9838,.9849,.9858,.9866,.9882,.9900,.9910,.9916,.9922,  
1 .9766,.9074,.9276,.9411,.9513,.9589,.9647,.9693,.9729,.9758,  
2 .9782,.9801,.9818,.9832,.9843,.9866,.9893,.9908,.9916,.9924,  
1 .9718,.9718,.9012,.9212,.9355,.9461,.9542,.9605,.9654,.9695,  
2 .9727,.9754,.9777,.9796,.9812,.9843,.9880,.9899,.9911,.9922,  
1 .8036,.8036,.8487,.8819,.9049,.9217,.9343,.9441,.9518,.9579,  
2 .9629,.9670,.9704,.9733,.9757,.9803,.9859,.9889,.9906,.9923,  
1 .8092,.8092,.8092,.8391,.8727,.8963,.9139,.9273,.9378,.9462,  
2 .9529,.9585,.9631,.9670,.9702,.9764,.9839,.9878,.9901,.9923,  
1 .7297,.7297,.7297,.7516,.8380,.8697,.8928,.9102,.9236,.9343,  
2 .9429,.9459,.9558,.9606,.9647,.9725,.9819,.9868,.9896,.9924,  
1 .7392,.7392,.7392,.7392,.8002,.8416,.8708,.8926,.9092,.9222,  
2 .9327,.9413,.9484,.9543,.9592,.9686,.9798,.9858,.9892,.9925,  
1 .6827,.6827,.6827,.7586,.8118,.8479,.8744,.8945,.9100,  
2 .9224,.9326,.9410,.9479,.9537,.9647,.9778,.9848,.9887,.9926,  
1 .6281,.6281,.6281,.6281,.7114,.7798,.8240,.8557,.8794,.8975,  
2 .9120,.9239,.9335,.9415,.9482,.9608,.9758,.9837,.9883,.9926/  
DATA((Z(J,K),J=1,20),K=10,17)/  
1 .6593,.6593,.6593,.6593,.6593,.7450,.7589,.8364,.8641,.8848,  
2 .9014,.9150,.9260,.9351,.9427,.9569,.9735,.9828,.9878,.9927,  
1 .6735,.6735,.6735,.6735,.6735,.7063,.7723,.8163,.8484,.8718,  
2 .8906,.9061,.9185,.9287,.9372,.9531,.9715,.9818,.9874,.9928,  
1 .6098,.6098,.6098,.6098,.6098,.6098,.7136,.7733,.8145,.8462,  
2 .8699,.8876,.9031,.9157,.9262,.9452,.9680,.9798,.9866,.9932,  
1 .4689,.4689,.4689,.4689,.4689,.4689,.6429,.7256,.7775,.8204,  
2 .8492,.8671,.8866,.9024,.9152,.9372,.9641,.9780,.9858,.9937,  
1 .3298,.3298,.3298,.3298,.3298,.3298,.5332,.6774,.7476,.7882,  
2 .8233,.8530,.8734,.8874,.9042,.9288,.9602,.9761,.9850,.9942,  
1 .3632,.3632,.3632,.3632,.3632,.3632,.3632,.6260,.7232,.7520,  
2 .7952,.8401,.8603,.8655,.8932,.9188,.9563,.9744,.9843,.9947,  
1 .5120,.5120,.5120,.5120,.5120,.5120,.5120,.5120,.6494,.7327,  
2 .7792,.8123,.8412,.8654,.8823,.9027,.9524,.9726,.9836,.9953,  
1 .6427,.6427,.6427,.6427,.6427,.6427,.6427,.6427,.6427,.6427,  
2 .7150,.7661,.8028,.8314,.8553,.9001,.9414,.9684,.9821,.9960/

```

C
C
C      IF (TX(20)-T) 11,13,13
C
C 11  Z7 = 1.0
C     Z1 = 1.0
C     Z2 = 1.0
C     RETURN
C
C 13  DO 17 J=1,19
C     JJ = 20 - J
C     IF (TX(JJ)-T) 15,15,17
C
C 15  NT = JJ
C     GO TO 19
C
C 17  CCNTINUE
C     GO TO 11
C
C 19  IF(P-PX(1)) 11,23,23
C 23  DO 27 J=2,17
C     IF (P-PX(J)) 25,25,27
C
C 25  NP = J-1
C     GO TO 31
C
C 27  CCNTINUE
C     GO TO 11
C
C 31  ZA = Z(NT,NP)+(P-PX(NP))/(FX(NP+1)-PX(NP))*(Z(NT,NP+1)-Z(NT,NP))
C
C     ZB = Z(NT+1,NP)+(P-PX(NP))/(PX(NP+1)-PX(NP))*
C 1    (Z(NT+1,NP+1)-Z(NT+1,NP))
C
C     ZZ = ZA + (T-TX(NT))/(TX(NT+1)-TX(NT))*(ZB-ZA)
C
C     CZDT = (ZB-ZA)/(TX(NT+1)-TX(NT))
C
C     Z1 = ZZ+T*CZDT
C
C     CZDP = (Z(NT,NP+1)-Z(NT,NP)+(T-TX(NT))/(TX(NT+1)-TX(NT))*
C 1    (Z(NT+1,NP+1)-Z(NT+1,NP)-Z(NT,NP+1)+Z(NT,NP)))/(PX(NP+1)-PX(NP))
C
C     Z2 = ZZ-P*CZDP
C
C     RETURN
C
C  END

```

```

SUBROUTINE HCOEFF (T,TTT,P,XL,H,PRAM,ZCCNST,HMULT,HEXP,XMOLEC)
C
C
C      DIMENSION VIY(2,7),VIX(2,7),COY(2,7),COX(2,7)
C
C      HYDROGEN VISCOSITY DATA ((LB)(SEC)/(SQ FT))
C      (DATA FROM HILSEN RATH, ET AL)
C      DATA(VIY(1,J),VIX(1,J),J=1,7)/ .1064E-7,18.,.6005E-7,108.,
1 1.001E-7,216.,1.324E-7,324.,1.654E-7,450.,1.954E-7,576.,
2 2.195E-7,684./
C
C      HYDROGEN THERMAL CONDUCTIVITY DATA (BTU/(SEC)(FT)(DEG R/FT))
C      (DATA FROM HILSEN RATH, ET AL)
C      DATA(COY(1,J),CCX(1,J),J=1,7)/ .1187E-5,18.,.6780E-5,108.,
1 1.268E-5,216.,1.871E-5,324.,2.505E-5,450.,3.075E-5,576.,
2 3.520E-5,684./
C
C      HELIUM VISCOSITY DATA (LB-SEC/SQ FT) (VANCE AND DUKE)
C
C      DATA (VIY(2,J),VIX(2,J),J=1,7)/ .376E-7,10.,.668E-7,30.,1.002E-7,
1 60.,1.420E-7,100.,2.257E-7,200.,3.528E-7,400.,6.075E-7,800./
C
C      HELIUM THERMAL COND DATA (BTU/SEC-FT-DEG R) (VANCE AND DUKE)
C
C      DATA (COY(2,J),CCX(2,J),J=1,7)/ .1806E-5,10.,.375E-5,30.,.597E-5,
1 60.,.834E-5,100.,1.277E-5,200.,2.E-5,400.,3.445E-5,800./
1 M = .5*XMOLEC
R = 1545.4
C = XMOLEC*P/R
C
C      TAV = 0.5*(T+TTT)
C      RHOSQ = (C/TAV)**2
C
C      DO 1 J=2,7
C      IF (TAV-VIX(M,J)) 3,3,7
C
C      3 VISC = VIY(M,J-1)+(TAV-VIX(M,J-1))/(VIX(M,J)-VIX(M,J-1))*
1 (VIY(M,J)-VIY(M,J-1))
GO TO 9
C
C      7 CONTINUE
C      VISC = VIY(M,7)
C
C      9 DO 15 J=2,7
C      IF (TAV-COX(M,J)) 11,11,15
C
C      11 COND = COY(M,J-1)+(TAV-COX(M,J-1))/(COX(M,J)-COX(M,J-1))*
1 (COY(M,J)-COY(M,J-1))
GO TO 17
C
C      15 CONTINUE
C      COND = COY(M,7)
C
C      17 CALL SPHEAT (TAV,TAV,CP,CPw,XMOLEC)
C

```

```

      TDIFF= ABS(TTT-T)
      IF (TDIFF-1.0) 19,23,23
19    TDIFF = 1.0
23    IF (ZCCNST) 27,27,25
25    BETA = 1.0/TAV
      GO TO 29
27    CALL CCMPRS(TAV,P,Z,Z1,Z2,XMCLEC)
      BETA = Z1/Z/TAV
29    XHOLD = ALOG(XL**3*RHOSQ*CP*TDIFF/VISC/COND*BETA)
      XHOLD = HEXP*XHOLD
      XHOLD = EXP(XHOLD)
C
      H = HMULT*(COND/XL)*XHOLD
      PVC = COND * ( 1.0/(32.17*VISC))**.8
      PDL = (CP * VISC/COND * 32.17)**.333
      PRAM = PDL * PVC
C
      RETURN
C
      ENF

```

```

SUBROUTINE INTERP (Y,X,M,ARG,ANS)
C
C
C   DIMENSION Y(100),X(100)
C
C   1   IF (M-1) 3,5,7
C   3   RETURN
C
C   5   ANS = Y(1)
C       RETURN
C
C   7   IF (ARG-X(1)) 5,5,9
C
C   9   DO 13 J=2,M
C       IF(ARG-X(J)) 11,11,13
C
C   11  ANS = Y(J-1)+(ARG-X(J-1))/(X(J)-X(J-1))*(Y(J)-Y(J-1))
C       RETURN
C
C   13  CONTINUE
C       ANS = Y(M)
C
C       RETURN
C
C       END

```

# OUTPUT FOR EXPULSION PROGRAM

SUBROUTINE WRITE 2

C

DIMENSION

```

1  TGAS(30),TIME1(30),PDATA(30),TIME2(30),
2  FLOW(30),TIME3(30),TSAT(30),TIME4(30),
3  TBULK(30),TIME5(30),QOUTD(30),TIME6(30),
4  CIND(30),TIME7(30),ZAV(150),
5  TWINC(30),DIST1(30),TGIND(30),DIST2(30),
6  X(150),T(150),TP(150),TW(150),TWP(150),V(150),
7  CP(150),CPW(150),H(150),Z(150),Z1(150),Z2(150),
8  RAD(150),AREA(150),YRAD(150),XRAD(150),DRDX(150)

```

DIMENSION

```

1  C5(150),C9(150),YTICK(50),XXT(50),TICK(150)
2  ,TWBK(30),DIST7(30),TWCU(30),DIST8(30),TSTN(30),DIST9(30),
3  TWAL(30),DIS11(30),CPBK(150),TWB(150),TB(150),CPCU(150),
4  TWC(150),TC(150),CPST(150),TST(150),TZ(150),CPAL(150),
5  TALS(150),TBC(150),TTT(150),PRAM(150)

```

C

COMMON

```

1  X,T,TP,TW,TWP,V,CP,CPW,TGAS,TIME1,MTGAS,PDATA,TIME2,MPDATA,
2  FLOW,TIME3,MFLOW,TSAT,TIME4,MTSAT,TBULK,TIME5,MTBULK,QOUTD,
3  TIME6,MQOUT,QIND,TIME7,MOIN,N,NP,XN,ULLAGE,RADIUS,DQ,
4  SPWGT,XMOLEC,GSTART,HCONST,TIME,GAS,Q,GASCHK,GSRATE,DT,
5  ZCONST,H,HPULT,HEXP,YRAD,XRAD,MRAD,TNKWT,COTR,QIN,UNUMS,
6  MTWIN,MTGIN,MTICK,MTBAK,MTCU,MTSS,MTAL,
7  TWIND,DIST1,TGIND,DIST2,YTICK,XXT,TWBK,DIST7,
8  TWAL,DIS11,TWCU,DIST8,TSTN,DIST9

```

C

COMMON

```

1  CARAD,ADIFU,SPWSS,DIA,RCONST,TADD,AB,A1C,A3S,A5B,WTB,WTIC,
2  WT3S,WT5B

```

C

```

IF(UNUMS .GT. 0.) GO TO 200
WRITE (6,1016) TIME,GAS,Q,V(2)

```

C

```

1016 FORMAT (1HL/1HL,9H TIME = F6.1,9H SECONDS,5X,17H GAS SUPPLIED =
1  F7.3,5H LBS,5X,17H HEAT TO WALL = F8.1,5H BTU,5X,
2  14H INLET VEL = F6.4,10H FEET/SEC)

```

C

```

WRITE (6,1017) COTR,GASCHK,GSRATE,QIN

```

C

```

1017 FORMAT (1HK,16H HEAT TO LIQ = F7.1,5H BTUS,3X,17H CHECK ON GAS =
1  F7.3,5H LBS,3X,13H GAS FLOW = F7.4,9H LBS/SEC,
2  3X,16H HEAT TO HARD = F6.4,13H BTU/(FT-SEC))

```

C

```

WRITE (6,1018)

```

C

```

1018 FORMAT (1HK,10H X, FEET,2X,11H WALL T(R),11H GAS T(R),7X,
1  10H X, FEET,2X,11H WALL T(R),11H GAS T(R),7X,10H X, FEET,
2  2X,11H WALL T(R),11H GAS T(R)/X)

```

C

```

WRITE (6,1020) (X(J),TWP(J),TP(J),J=1,NP)

```

```

1020 FORMAT (F10.2,F12.1,F12.1,F17.2,F12.1,F12.1,F17.2,F12.1,F12.1)

```

C

```

RETURN

```

```

200 CONTINUE

```

```

      DO 201 J=1,NP
      X(J)= X(J)*0.3048
      TP(J)= TP(J)/1.8
      TwP(J)= TwP(J)/1.8
201  CONTINUE
      GAS = GAS * 0.45359237
      RT = Q * 1054.3503
      V(2)= V(2)*0.3048
      COLA = CQTR * 1054.3503
      DBLCK = GASCHK * 0.45359237
      GSRATE = GSRATE * 0.45359237
      QIN= CIN * 3459.1475
      WRITE (6,300) TIME,GAS,RT,V(2)
300  FORMAT (1HL/1HL,9H  TIME = F6.1,9H  SECCNDS,5X,16H GAS SUPPLIED =
      1F7.4,9H KILOGRAM,1X,17H  HEAT TO WALL = E11.4,6H JOULE,1X,14H  INL
      2ET VEL = F6.4,10H METER/SEC)
      WRITE (6,305) COLA,DBLCK,GSRATE,QIN
305  FORMAT (1HK,16H  HEAT TO LIQ = E12.5,2H J,1X,17H  CHECK ON GAS = F
      17.3,4H  KG,4X,13H  GAS FLOW = F7.4,8H  KG/SEC,1X,16H HEAT TO HARD
      2= E11.4,10H J/(M-SEC))
      WRITE (6,310)
310  FORMAT (1HK,10H  X, METER,1X,13H  WALL TEMP-K,14H  GAS TEMP-K,3X
      1,10H  X, METER,1X,13H  WALL TEMP-K,14H  GAS TEMP-K,3X,10H  X, ME
      2TER,1X,13H  WALL TEMP-K,14H  GAS TEMP-K/1X)
      WRITE(6,311) (X(J),TwP(J),TP(J),J=1,NP)
311  FORMAT (F10.4,F12.1,F12.1,F17.4,F12.1,F12.1,F17.4,F12.1,F12.1)
210  CONTINUE
      DO 211 J=1,NP
      X(J) = X(J)/.3048
      TP(J) = TP(J) * 1.8
      TwP(J) = TwP(J) * 1.8
211  CONTINUE
      GAS = GAS / 0.45359237
      V(2) = V(2)/.3048
      QIN = CIN/3459.1475
C
      RETURN
C
      END

```



# OUTPUT FOR RAMP PROGRAM

```

SUBROUTINE WRITE2
C
  DIMENSION TGAS(100), TIME1(100), PDATA(100), TIME2(100), FLCW(25),
1 TIME3(25), TSAT(50), TIME4(50), TBULK(25), TIME5(25), COUTD(25),
2 TIME6(25), QIND(25), TIME7(25), ZAV(250), TWIND(100), DIST1(100),
3 TGIND(100), DIST2(100), X(250), T(250), TP(250), TW(250), TWP(250)
4, V(250), VP(250), CP(250), CPW(250), H(250), Z(250), Z1(250), Z2(
5250), RAD(250), AREA(250), YRAD(250), XRAD(250), DRGX(250), TEST(2
650)
  DIMENSION C5(250), C9(250), YTICK(250), XXT(250), TICK(250), XR(3)
1, AQ(3)
C
  COMMON X,T,TP,Th,TWP,V,CP,CPW,TGAS,TIME1,MTGAS,PDATA,TIME2,MPDATA,
1 FLOW,TIME3,MFLOW,TSAT,TIME4,MTSAT,TBULK,TIME5,MTBULK,QOUTD,TIME6,M
2 QOUT,QIND,TIME7,MQIN,N,NP,XN,ULLAGE,RADIUS,TLID,SPWGT,XMOLEC,GSTAR
3 T,HCONST,TIME,GAS,Q,GASCHK,GSRATE,DT,ZCONST,H,HMULT,HEXP,YRAD,XRAD
4,MRAD,DQ,QIN,UNUMS,TWIND,DIST1,MTWIN,TGIND,DIST2,MTGIN,DIA,
5 TADD,YTICK,XXT,MTICK
C
  IF(UNUMS .GT. 0.) GO TO 200
  WRITE (6,1) TIME,GAS,Q,V(1)
C
C
  WRITE (6,2) GASCHK,GSRATE,V(NP)
C
C
  WRITE (6,3)
C
C
  WRITE (6,4) (X(J),TWP(J),TP(J),J=1,N)
C
  RETURN
200 CONTINUE
  DO 201 J=1,N
  X(J)= X(J)*0.3048
  TP(J)= TP(J)/1.8
  TWP(J)= TWP(J)/1.8
201 CONTINUE
  GAS= GAS * 0.4535924
  Q = Q * 1054.3503
  V(1) = V(1) * 0.3048
  GASCHK= GASCHK * 0.4535924
  GSRATE= GSRATE * 0.4535924
  WRITE (6,300) TIME,GAS,Q,V(1)
  WRITE (6,305) GASCHK,GSRATE,V(NP)
  WRITE (6,310)
  WRITE (6,311) (X(J),TWP(J),TP(J),J=1,N)
210 CONTINUE
  DO 211 J=1,N
  X(J) = X(J)/.3048
  TP(J) = TP(J) * 1.8
  TWP(J) = TWP(J) * 1.8
211 CONTINUE
  GAS = GAS/.4535924
  Q = Q/1054.3503

```

```

V(1) = V(1)/.3048
GASCHK = GASCHK/.4535924
GSRATE = GSRATE/.4535924
RETURN

```

C  
C  
C

```

1  FORMAT (1HL/1HL,9H TIME = F6.2,9H SECONDS,5X,17H GAS SUPPLIED =
1  F7.4,5H LBS,5X,17H HEAT TO WALL = F8.1,5H BTU,5X,14H INLET VE
1  2L = F6.4,10H FEET/SEC)
2  FORMAT (1HK,16X,17H CHECK ON GAS = F7.3,5H LBS,5X,13H GAS FLOW
1  1= F7.4,9H LBS/SEC,5X,15H OUTLET VEL = F6.4,10H FEET/SEC)
3  FORMAT (1HK,10H X, FEET,2X,11H WALL T(R),11H GAS T(R),7X,10H
1  1 X, FEET,2X,11H WALL T(R),11H GAS T(R),7X,10H X, FEET,2X,11H
2  2 WALL T(R),11H GAS T(R)/1X)
4  FORMAT (F10.2,F12.1,F12.1,F17.2,F12.1,F12.1,F17.2,F12.1,F12.1)
300 FORMAT (1HL/1HL,9H TIME = F6.1,9H SECONDS,5X,16H GAS SUPPLIED =
1  F7.4,5H KILOGRAM,1X,17H HEAT TO WALL = E11.4,6H JOULE,1X,14H INL
2  2ET VEL = F6.4,10H METER/SEC)
305 FORMAT (1HK,16X,17H CHECK ON GAS = F7.3,4H KG,6X,13H GAS FLOW =
1  F7.4,9H KGS/SEC,5X,15H OUTLET VEL = F6.4,11H METER/SEC)
310 FORMAT (1HK,10H X, METER,1X,13H WALL TEMP-K,14H GAS TEMP-K,3X
1  1,10H X, METER,1X,13H WALL TEMP-K,14H GAS TEMP-K,3X,10H X, ME
2  2TER,1X,13H WALL TEMP-K,14H GAS TEMP-K/1X)
311 FORMAT (F10.2,F12.1,F12.1,F17.2,F12.1,F12.1,F17.2,F12.1,F12.1)
END

```

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4. Stochl, Robert J.; Masters, Philip A.; DeWitt, Richard L.; and Maloy, Joseph E.: Gaseous-Hydrogen Pressurant Requirements for the Discharge of Liquid Hydrogen from a 3.96-Meter - (13-ft-) Diameter Spherical Tank. NASA TN D-5387, 1969.
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8. Nein, M. E.; and Thompson, J. F.: Experimental and Analytical Studies of Cryogenic Propellant Tank Pressurant Requirements. NASA TN D-3177, 1966.

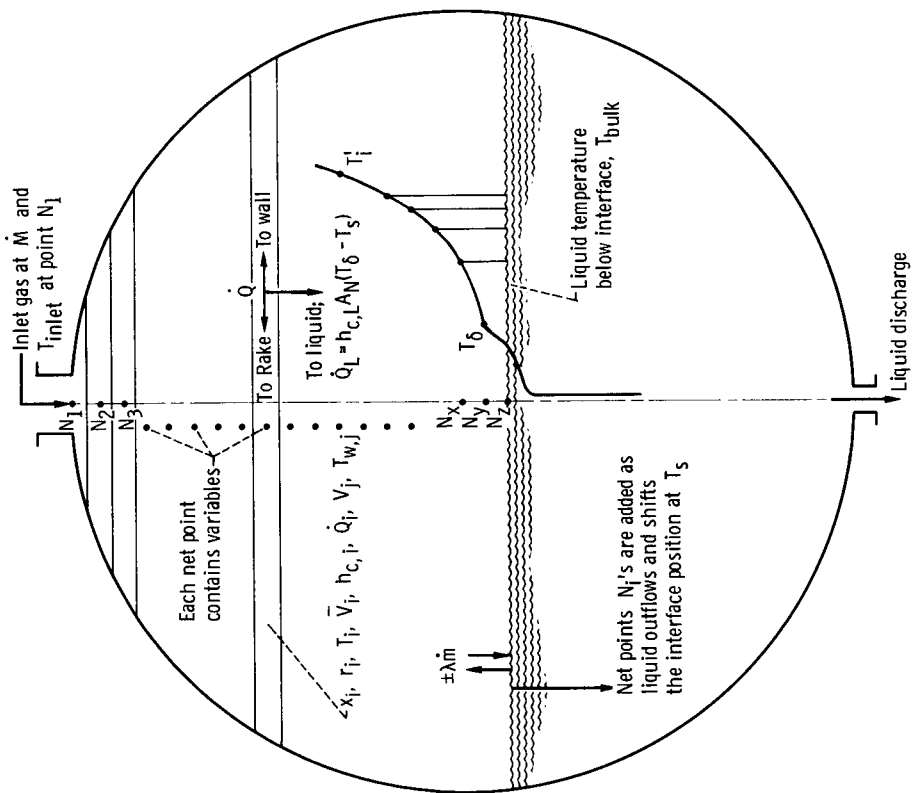


Figure 1. - Analytical model. Coordinate system is positive in the downward direction from  $x = 0$  at  $N_1$  to  $x = n$  at the interface  $N_2$ .

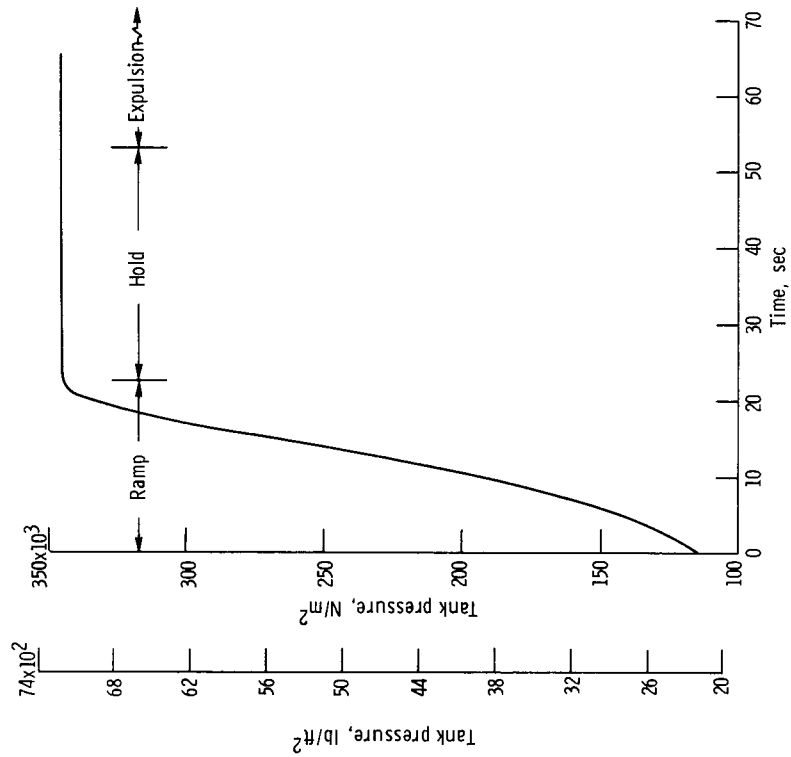


Figure 2. - Typical curve showing tank pressure as function of time during initial pressurization period.

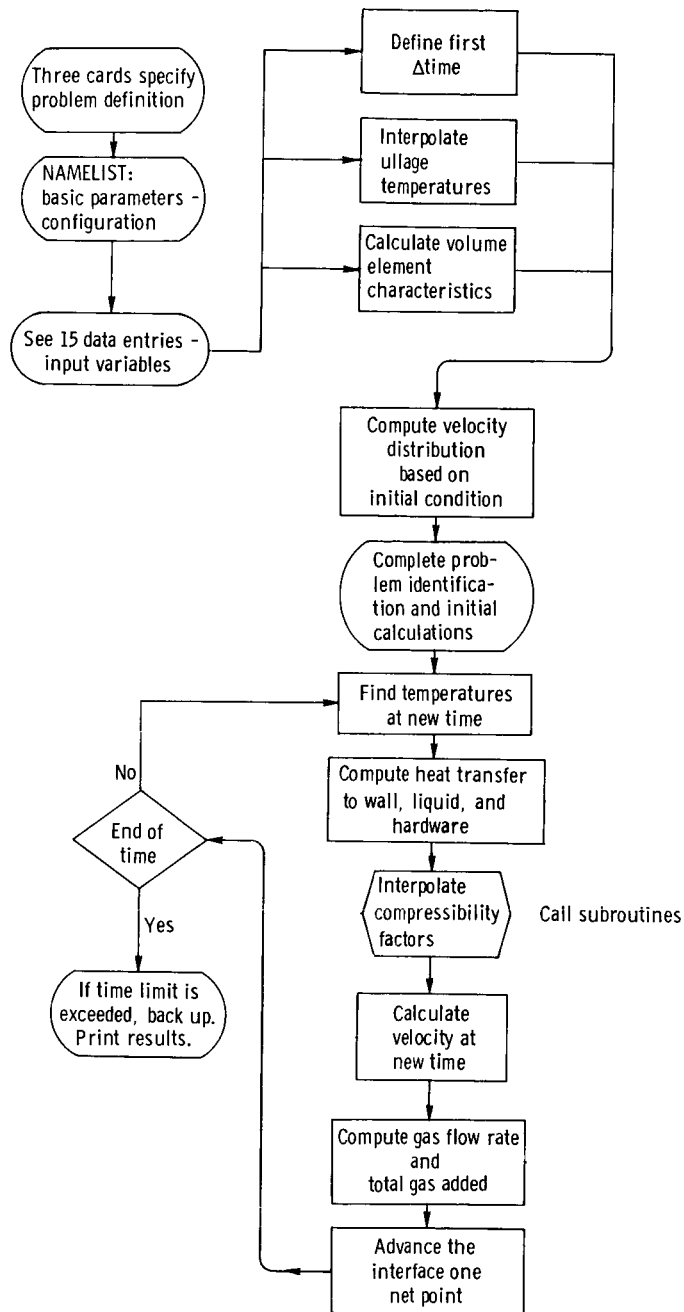


Figure 3. - Logic diagram of expulsion program.

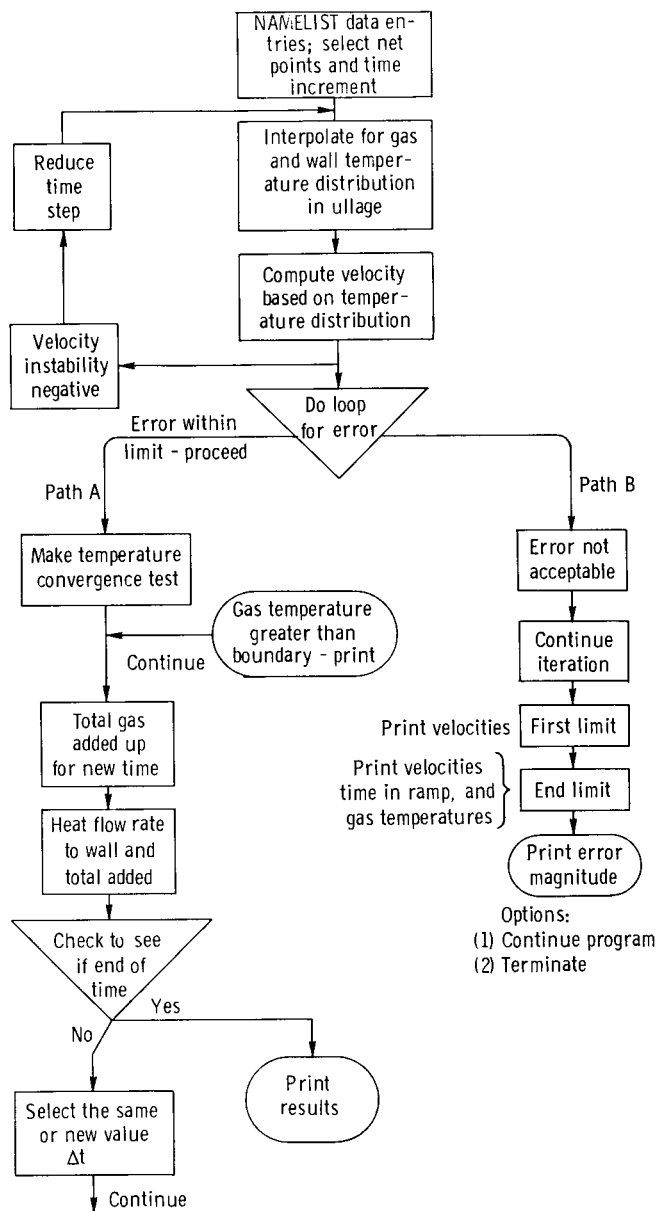


Figure 4. - Logic diagram of ramp program.

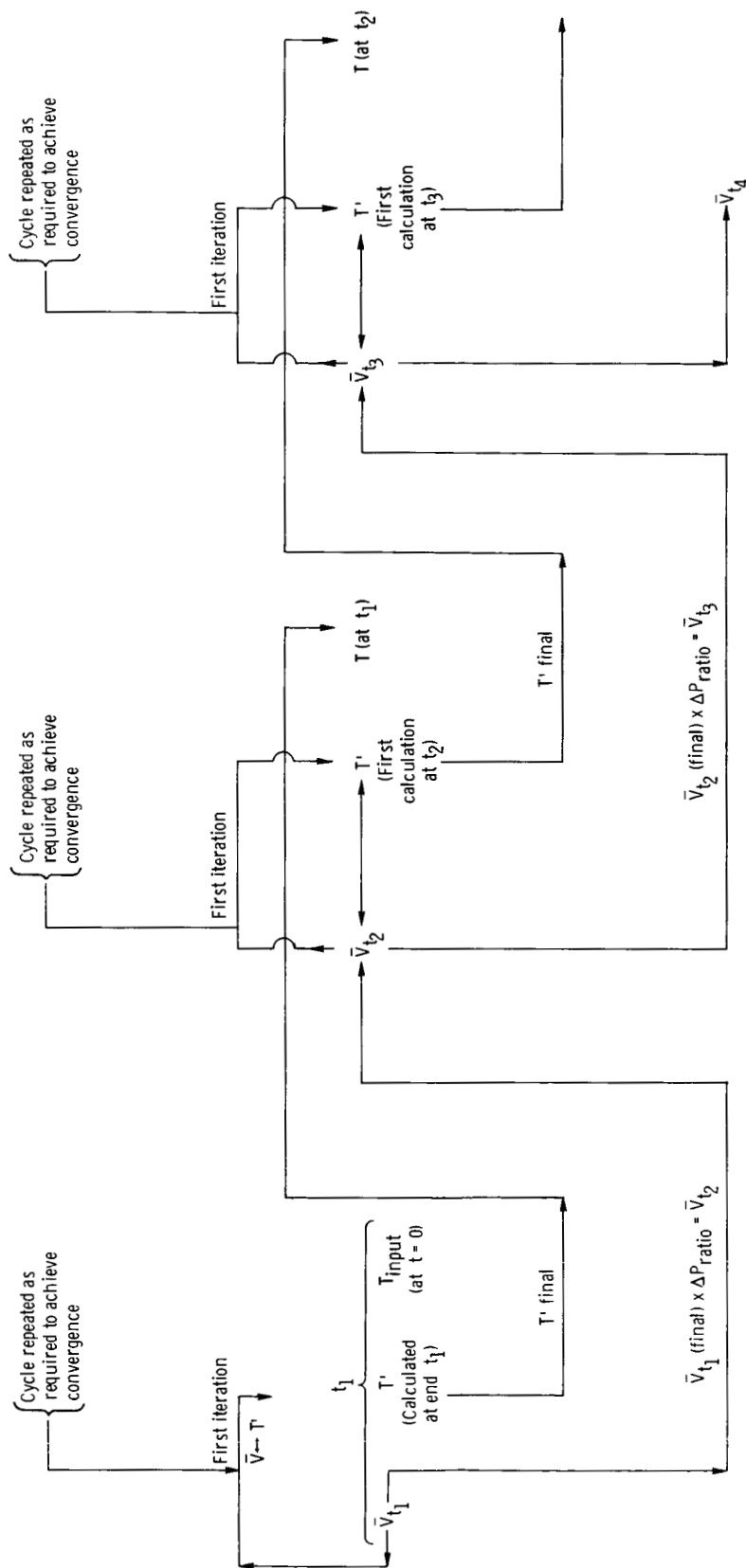


Figure 5. - Flow diagram showing temperature-velocity iteration in energy and continuity equations.